DTRA-TR-13-047

TECHNICAL REPORT

ZEPrompt: An Algorithm for Rapid Estimation of Building Attenuation for Prompt Radiation from a Nuclear Detonation

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January 2014

Prepared by:

Human Survivability Research and Development Integrated Program Team

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 31-01-2014	**2. REPORT TYPE** Technical Report	**3. DATES COVERED *(From – To)***
4. TITLE AND SUBTITLE ZEPrompt: An Algorithm for Rapid Estimation of Building Attenuation for Prompt Radiation from a Nuclear Detonation		**5a. CONTRACT NUMBER** DTRA01-03-D-0014-0038 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Kevin Kramer, Kyle Millage, and Brian Sanchez		**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Applied Research Associates, Inc. 801 N. Quincy St., Suite 700 Arlington, VA 22203		**8. PERFORMING ORGANIZATION REPORT NUMBER** DTRA-TR-13-047
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Threat Reduction Agency 8725 John J. Kingman Road, MS 6201 Fort Belvoir, VA 22060-6201		**10. SPONSOR/MONITOR'S ACRONYM(S)** DTRA/J9NTSN **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report describes an estimation algorithm called ZEPrompt developed to assess the effects of urban terrain on prompt radiation transport and propagation. The ZEPrompt algorithm is a parameterization of data from an ensemble of artificial city models for the purpose of creating a fast-running estimate of the prompt neutron and photon dose in an urban environment given the urban geometry and an open-field calculation of the source term. The ZEPrompt tool is demonstrated to calculate the radiation level ground range to mean contours of 0.05 Gy, for detonations between 5 kT and 50 kT, to within 30% of first-principles code (MCNP) for complicated cities and 10% for simpler cities.

15. SUBJECT TERMS
Radiation Transport, Nuclear Detonation, Initial Radiation, Urban Terrain, Dose Estimate

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**a. THIS PAGE**	Unlimited	51	Paul K. Blake, PhD
U	U	U			**19b. TELEPHONE NUMBER** (include area code) *703 767-3433*

Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std. Z39.18

UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by → / ← Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
Energy/Work/Power			
electronvolt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kT) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Temperature			
degree Fahrenheit (°F)	[T(°F) − 32]/1.8		degree Celsius (°C)
Radiation			
absorbed dose (rad)	1	$\times 10^{-2}$	J kg^{-1}§
equivalent and effective dose (rem)	1	$\times 10^{-2}$	J kg^{-1}**

* Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

† Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

§ The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J kg^{-1}).

**** The special name for the SI unit of equivalent and effective dose is the sievert (Sv). (1 Sv = 1 J kg^{-1})**

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Executive Summary

This report describes an estimation algorithm called ZEPrompt developed to rapidly assess the effects of urban terrain on prompt neutron and initial gamma radiation transport and propagation. High-fidelity modeling has shown that both air-blast and prompt radiation transport and propagation will be significantly affected by urban terrain. As a result, use of historical models that do not account for urban terrain effects will likely overestimate the range of both blast and radiation and therefore will overestimate casualties. The ZEPrompt algorithm uses fits to data from an ensemble of artificial city models to create a fast-running estimate of the prompt neutron and initial photon dose in an urban environment given the urban geometry and an open-field calculation of the source

The initial version of the tool is designed to calculate the dose outside of buildings in an urban environment for a one-meter height-of-burst detonation over an approximately level concrete surface. These calculations approximate the radiation from neutrons and photons that are released before the weapon disassembles. The radiation from other sources, including delayed radiation, is not included in the ZEPrompt algorithm.

The output is a set of attenuation factors that can be used in conjunction with the absorbed dose of an open-field one-meter height-of-burst detonation to estimate urban external absorbed dose. This initial set of attenuation factors are not intended to predict results from higher heights of burst or over large altitude variations in the terrain. The ZEPrompt tool was developed to calculate the radiation level contours out to a ground range associated with approximately 0.05 Gy for detonations between 5 kT and 50 kT. Based on the comparisons with high-fidelity (MCNP) calculations, the results from ZEPrompt are within 30% of first-principles code for complicated cities and 10% for simpler cities. The results from ZEPrompt are intended to be used in a fast-running tool when high-fidelity results are not immediately required; for example, casualty estimation and emergency-response planning.

While detailed simulations of radiation transport will continue to require long computation times and a high level of technical proficiency, ZEPrompt brings the capability to estimate doses in urban areas to a broader user community.

Section 1.

Introduction

Classic models of nuclear weapon effects, many of which are benchmarked to results from the above-ground testing program, generally provide a good estimate of the effects of a nuclear weapon detonated over a flat open plane. Further, the majority of the tests were conducted at altitude rather than near the surface as optimization of air-blast propagation was one of the primary objectives. In contrast, a low-yield ground detonation in an urban setting is of concern in today's political environment (Office of Science and Technology Policy, 2010). High-fidelity modeling has shown that both air-blast and prompt radiation transport and propagation will be significantly affected by urban terrain. As a result, use of historical models that do not account for urban terrain effects will likely overestimate the range of both blast and radiation and therefore will overestimate casualties.

The Defense Threat Reduction Agency (DTRA), Human Survivability Research and Development (HSRD) Integrated Program Team (IPT), consisting of military, civilian, and contract scientists has developed modeling tools to account for urban terrain effects. The radiation transport calculations described in this report are derived from detailed urban environment models used in the radiation transport code Monte Carlo N-Particle (MCNP) (X-5 Monte Carlo Team, 2008), which consist of three-dimensional lattice of elements representing air, ground and buildings. Each building contains internal structures of gypsum walls, concrete slab floors and ceilings. The model has a layered atmosphere that accounts for variation in atmospheric composition to accurately account for sky-shine, the atmospheric scattering of radiation.

Though these MCNP models are the state-of-the-art method for modeling prompt radiation transport, the calculations require thousands of hours of computer resources to produce useful results. The purpose of the work presented in this report is to create a fast-running method which reproduces the ground range to mean dose contours of the detailed Monte Carlo calculations. The goal for these calculations is to be adequate for casualty estimation and emergency response planning. A relative error between the fast running tools mean contour distance and the high-fidelity simulation mean contour distance of 10-30% would be a significant improvement over current engineering-level code capabilities. The results are not intended to support detailed work in which a high-fidelity calculation would be more appropriate.

The software detailed in this report is designed to calculate the dose outside of buildings in an urban environment for a one-meter height-of-burst detonation over an approximately level concrete surface. The output is a set of attenuation factors that can be used in conjunction with the absorbed dose of an open-field one-meter height-of-burst detonation to estimate urban external absorbed dose. This initial set of attenuation factors are not intended to predict results from higher heights of burst or over large altitude variations in the terrain.

Section 2.

Algorithm Methodology

2.1 Overview

The algorithms in ZEPrompt were developed by parameterizing the attenuation coefficients from a large ensemble of MCNP calculations of urban environments that form absorbed dose maps of a large range of potential urban geometries. This ensemble is designed to encompass a sufficiently broad range of urban environments to make the parameterization able to quickly estimate the prompt radiation in environments for which the full MCNP calculations have not been performed. The attenuation factors relate the dose in the urban environment to dose at the same range from ground zero in an open-field calculation, represented as the urban-to-open-field ratio.

ZEPrompt currently uses MCNP generated open-field dose calculations, created by assuming the detonation occurs at 1 meter above an infinite homogeneous plane of concrete and represents the estimated dose that would be present in the map area if there were no buildings. The urban terrain calculation requires a 3-dimensional map of the urban environment and user selected inputs to quickly estimate a resulting dose map. The urban terrain maps contain three-dimensional geometry description of the buildings present in the urban area. Geometries derived from National Geospatial Intelligence Agency (NGA) shapefiles were used for testing; however, any description of building heights and footprints placed on level ground could be used.

The user input consists of a selection of the detonation location, the overall source scaling factor, and the output spatial resolution. The source scaling factor is a linear multiplicative factor that scales the open-field calculation to represent the desired yield of the weapon. For instance, an open-field calculation dose for 1 kT might be used to get the dose of a 10 kT detonation by using a scaling factor of 10. The number of circular sectors, or “pie slices” (described later in this report), along with the radial range of the calculation, is used to determine the spatial resolution. The calculation process is shown in Figure 2-1.

To calculate an absolute dose, the urban-to-open-field ratio, the open-field source calculation, and the source scaling factor are multiplied. The urban-to-open-field ratio calculated by this method depends only on the urban geometry. The resulting output consists of maps of the outside-of-building neutron and photon prompt radiation dose at one-meter above ground level.

2.2 Use of MCNP for Dose Calculations

Both the open-field and urban environment dose calculation results presented in this report were calculated with the Monte-Carlo radiation-transport code MCNP5, v1.60. MCNP5 was chosen because it is a highly regarded first-principles radiation transport code that has been benchmarked against a large amount of experimental data (Los Alamos National Laboratory, 2010). MCNP5 was selected over MCNPX and MCNP6 because the computational efficiency was higher in MCNP5 than in the more general MCNP codes, and the additional features of MCNPX and MCNP6 were not necessary for these simulations.

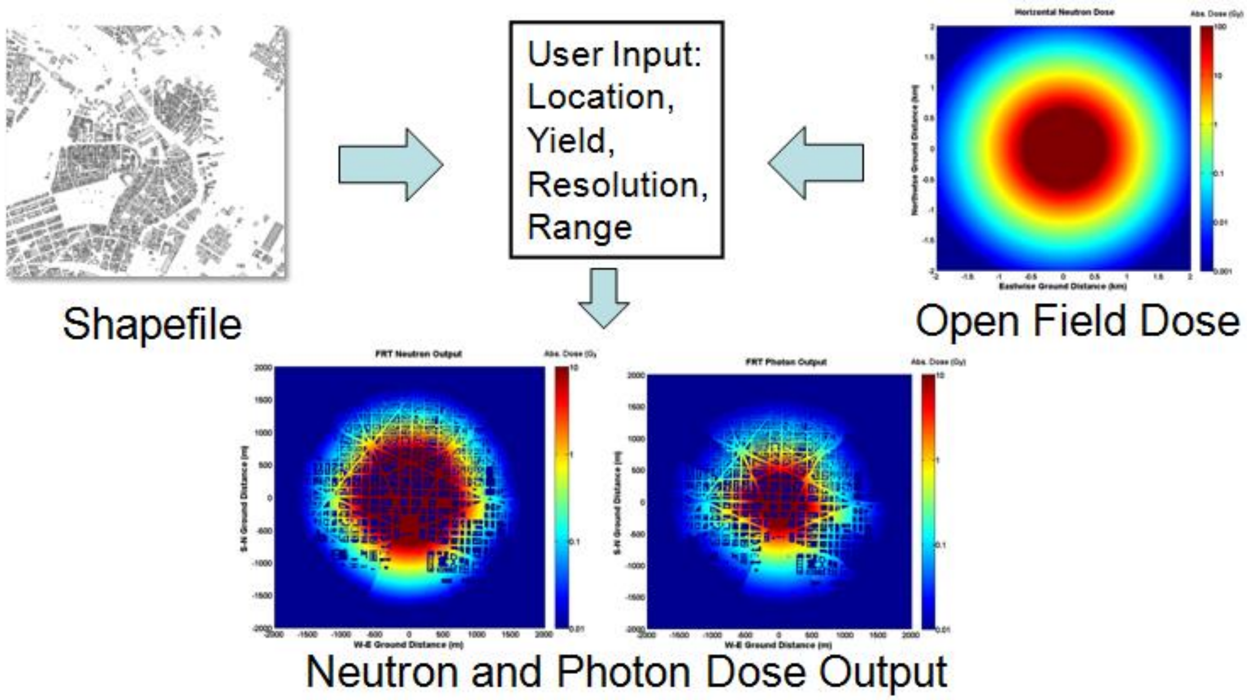

Figure 2-1. A descriptive diagram of the fast-running tool process

The simulations were run on the Department of Defense High-Performance Computing (HPC) systems, which are large assemblies of parallelized computer processors. On the HPC system, MCNP5 can take advantage of the message passing interface (MPI) to run in parallel. A typical single urban scenario simulation, with 10 billion source event histories for the neutron and photon source simulations plus set-up runs, requires approximately 6000 CPU-hours total. The large number of Monte Carlo calculations provides an absorbed-dose statistical error of less than 5% in areas where the total dose is greater than 0.05 Gy and less than 20% everywhere else outside of buildings.

A detailed description of the variance reduction techniques used for these simulations and other technical details of the MCNP code use are described in "Monte Carlo Modeling of the Initial Radiation Emitted by an Improvised Nuclear Device in the National Capital Region." (Kramer K. M., 2013)

2.3 MCNP Open-Field Absorbed Dose Calculations

ZEPrompt uses a pre-calculated open-field absorbed dose calculation and depends on the source energy distribution, choice of flux-to-dose conversion, atmospheric parameters (composition, structure and density) and ground parameters (density and composition). While there are several methods of calculating the absorbed dose in an open field, the work presented here used high-fidelity, open-field MCNP calculations to provide the open-field dose map input. This method was chosen due to the accuracy of a first-principles Monte Carlo calculation and the simplicity of the geometry set-up in MCNP as opposed to an analytical method or another transport code.

The sources used in this work are the unclassified sources described in ARA/HS-TN-12-004-A (Kramer K. M., 2012). In particular, two sources were used for testing: an unshielded

fission weapon spectrum from MCNP4 simulations (Terrell, 1990) and an isotropic version of the ‘Little Boy’ source from the RERF DS02 study (White, 2001). Figure 2-2 shows an example of neutron and photon absorbed dose distribution from an MCNP5 run from the unshielded fission source. The flux-to-dose conversion uses the ICRP-21 (International Commision on Radiological Protection, 1973) soft tissue absorbed dose for both neutrons and photons, with no quality factors (factors that are used to approximate the difference in biological damage caused by a dose from neutrons versus a dose from photons) applied to the neutron absorbed dose. Plots of the source spectra and the normalizations used are given in Appendix A.

All these sources describe the neutrons and photons released before the weapon disassembles. The delayed radiation from the decay of fission fragments and other sources of radiation are not included in any of these calculations even though they are important source of radiation from a nuclear event. Due to the complexity of calculating radiation from a moving, expanding source, the creators of ZEPrompt decided to not include this important quantity in this initial fast-running methodology.

The open-field absorbed dose in this report is represented in 801 x 801 mesh with each mesh element, or tally, a 5-m x 5-m x 1-m rectangular volume centered at 1-m above the ground. The simulation source was one meter above a concrete surface. The atmosphere uses a layered 1976 atmospheric model (Kramer K. M., 2013).

The technique used in the ZEPrompt algorithm uses the same attenuation coefficients independent of the source. Since different sources would have different distributions of neutron and photon energies, differences between the attenuation coefficients from different sources would be expected. Results from different sources and their combined effect on the algorithm uncertainty are shown in Section 3.

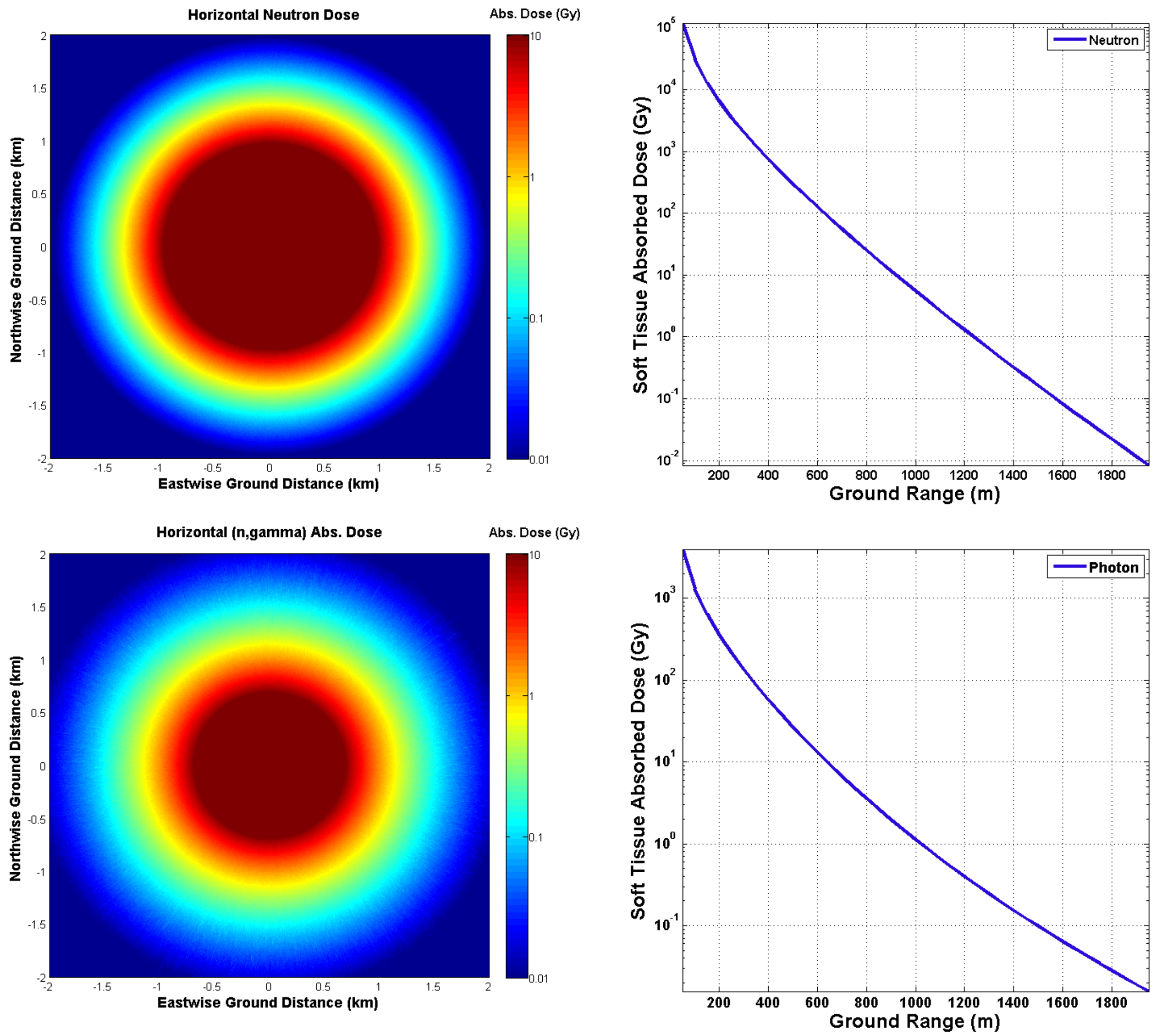

Figure 2-2. Plot of MCNP5 mesh tally of neutron and photon soft-tissue absorbed dose of 10-kT open-field unshielded fission-type detonation at a 1-m height-of-burst over concrete

2.4 The MCNP Urban Model

Buildings are represented in three dimensions by walls, windows, ceilings, floors, interior dry wall and other structural material, as shown in Figure 2-3. Specific urban geometries are extracted from shapefiles from National Geospatial Intelligence Agency (NGA). Additional information about building types come from the FEMA Hazus dataset (Federal Emergency Management Agency, 2003). An example representation of a portion of Manhattan used in this work is shown in Figure 2-4; a detailed description of the ARA 3-D urban models is presented in “Monte Carlo Modeling of the Initial Radiation Emitted by an Improvised Nuclear Device in the National Capital Region” (Kramer K. M., 2013). The elevation maps of the four models of real cities used in this report are given in Appendix B.

In addition to models of actual cities, artificially created cities were used to test the algorithm against specific situations. These artificial cities were created with the same building

elements as the urban models, such as ceilings, floors and walls, , but the buildings are more evenly distributed to tests the algorithm's sensitivity to certain parameters. An example of an artificially created city is shown in Figure 2-5; this example includes a central city section that includes a cluster of tall buildings surrounded by a wide expanse of shorter buildings. This simple representation is a generalized representative of many cities. A description of the artificial city models used in this analysis is given in Appendix C.

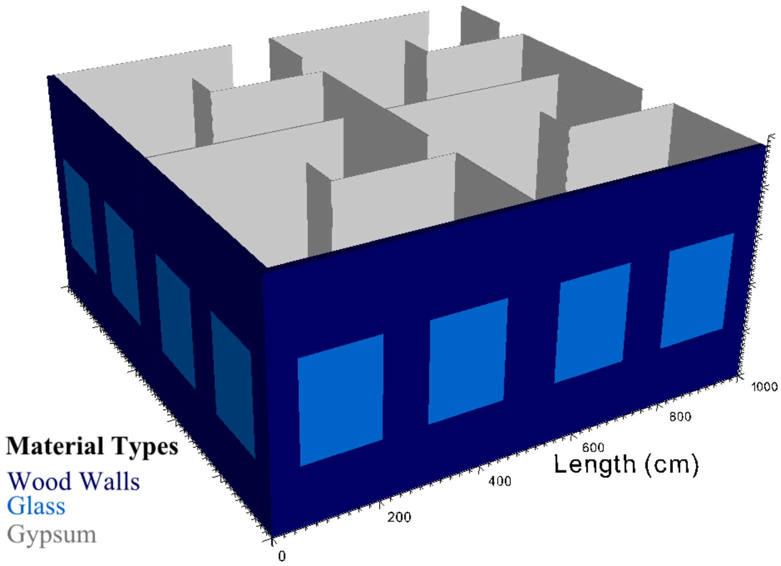

Figure 2-3. A depiction of one building type used in the HSRD IPT MCNP urban model

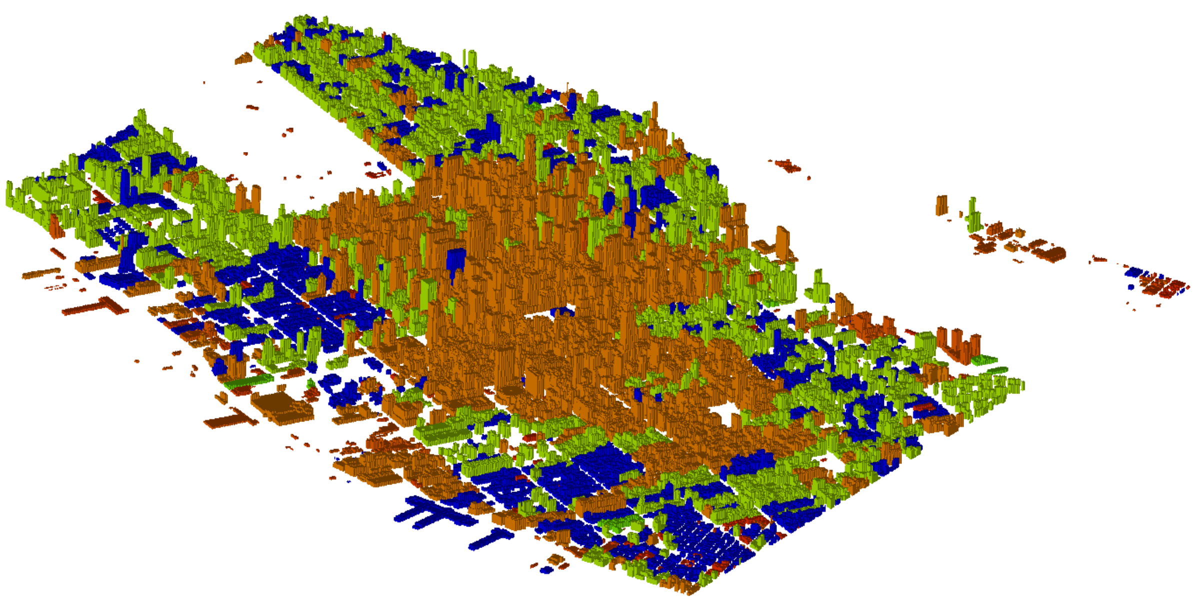

Figure 2-4. This is a representation of our 3-D urban MCNP model of a portion of Manhattan in New York City. The different colors of buildings correspond to the different FEMA Hazus building types used in the model.

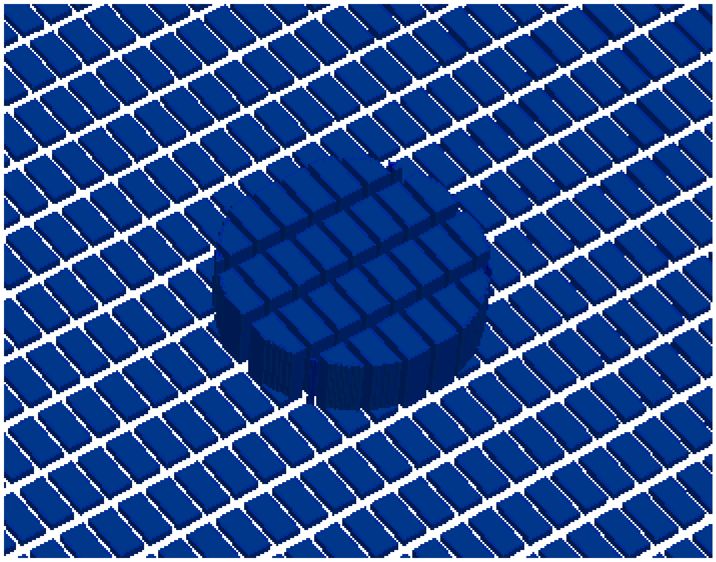

Figure 2-5. A section of an artificially created urban environment with a set of 170 m tall buildings in the center surrounded by 15 m tall buildings.

2.5 Average Zone Elevation

The ZEPrompt algorithm uses a combination of building elevation and ground area to form a quantity referred to as average zone elevation (AZE). The term elevation in this context refers to geometric height above the ground which, in our models, is a flat, concrete surface. The zone refers to a circular sector, or wedge, centered at the detonation location. The AZE is the average elevation of the defined zone where the elevation includes building and ground areas.

In the example shown in Figure 2-6, two zones from the same detonation location are shown. The first zone extends out to a radius of approximately 250 m and the second zone extends from the origin to a radius of 600 m, including the first zone.

In an ideal form the average zone elevation is calculated using:

$$\overline{\mathrm{E}}(r_l, \theta_{\min}, \theta_{\max}, x_\circ, y_\circ) = \frac{\int_0^{r_l} \int_{\theta_{\min}}^{\theta_{mex}} H(r\cos(\theta) + x_\circ, r\sin(\theta) + y_\circ) r d\theta dr}{\int_0^{r_l} \int_{\theta_{\min}}^{\theta_{mex}} r d\theta dr} \qquad (1)$$

where $\bar{E}(r_l, \theta_{min}, \theta_{max}, x_\circ, y_\circ)$ is the average zone elevation within a sector with its origin at $x_\circ$ and $y_\circ$, an angular range from $\theta_{min}\ to\ \theta_{max}$ and a maximum radius of r_l. $H(x, y)$ is the elevation given as a function of 2-D Cartesian coordinates, r_l is the ground distance from the detonation location and $x_\circ$ and $y_\circ$ are the detonation location in the coordinate system used by $H(x, y)$. However, $H(x, y)$ is not provided as a continuous function, but as a gridded 2-D elevation map with elevations given for each discrete pixel. In that case, an approximate method is used:

$$\overline{\mathrm{E}}(r_l,\theta_{\min},\theta_{\max},x_\circ,y_\circ)=\frac{1}{N_r}\sum_{i=1}^{N_r}\frac{1}{N_\theta}\sum_{j=1}^{N_\theta}H(i\Delta r\cos(j\Delta\theta+\theta_{\min})+x_\circ,i\Delta r\sin(j\Delta\theta+\theta_{\min})+y_\circ) \quad (2)$$

where N_r is the number of radial samples, N_θ is the number of angular samples, $\Delta r = r_l/N_r$ and $\Delta\theta = (\theta_{max} - \theta_{\min})/N_\theta$. For most of the calculations in this report the number of radial and angular samples were chosen so that $\Delta r = 5$ m and $\Delta\theta = 0.01$ degrees. More sophisticated sample techniques will work with this formulation of the average zone elevation, but this method was chosen for simplicity while maintaining sufficient accuracy.

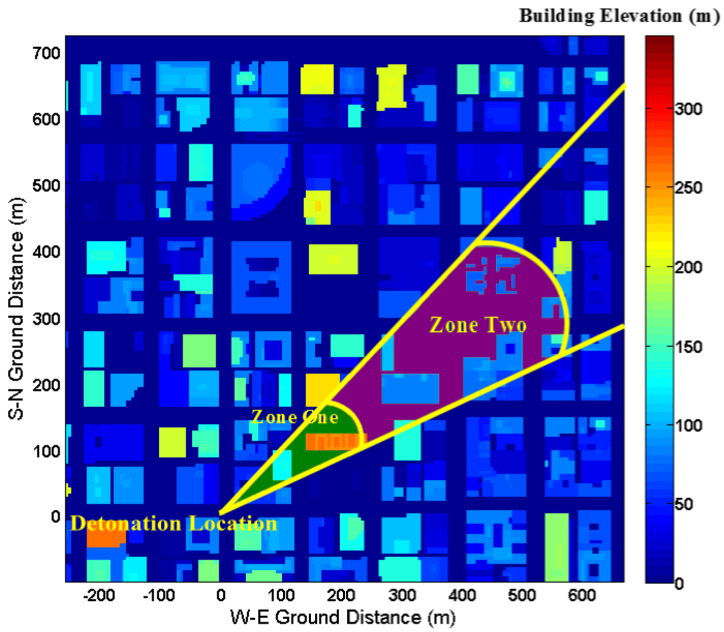

Figure 2-6. A graphic explanation of average zone elevation

2.6 Relationship between Average Zone Elevation and Urban to Open Field Ratio

The most general way of estimating dose from a nuclear detonation in an urban environment is to assume the existence of an open-field calculation for each source and then to apply a coefficient that estimates the relationship between the dose profile in the urban setting as related to the dose profile in the open calculation. A relation between the urban-to-open-field ratio and the average zone elevation would be expected since taller buildings block the direct radiation as well as scattered radiation. Most of the radiation outside a few blocks from ground zero is scattered from above and around the buildings, so the height of the buildings should also affect the urban-to-open field ratio.

Figure 2-7 is a plot of the urban-to-open-field ratio versus the average zone elevation for three different urban scenarios, New York City (in Times Square), Washington, DC (at 16th and K Street) and Chicago (W. Monroe St. and S. LaSalle). The dose maps were broken into 8 circular sectors with a maximum range of two km. Dose included in this plot excludes dose along road areas or areas of open space near the target because the radiation trends are significantly different in these areas relative to the surrounding areas.

Though the data is complex, there is a clear trend of decreasing urban-to-open field ratio with increasing average zone elevation. The goal of this work is to establish a set of functions and parameters to reproduce the trends in this data set so that it may be used in a general way to describe the urban-to-open field ratio in other urban nuclear detonation scenarios.

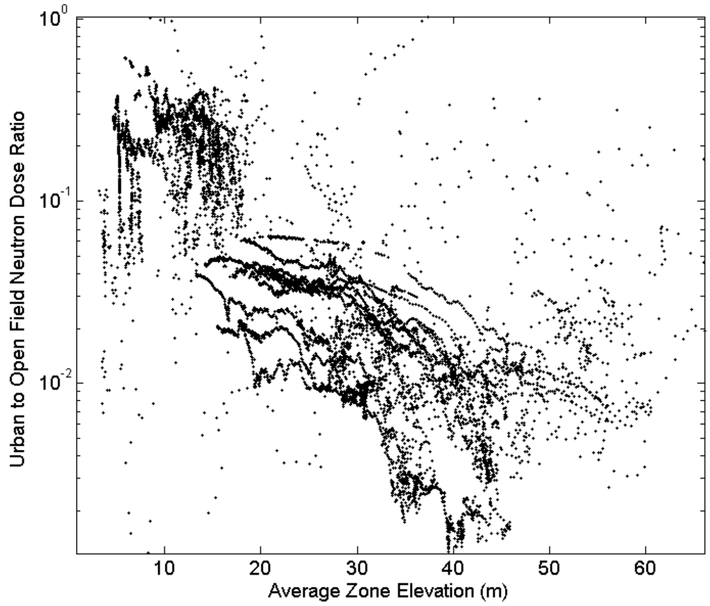

Figure 2-7. Relation between average zone elevation and urban-to-open-field neutron dose ratio for Washington, DC, New York City and Chicago prompt radiation scenarios

2.7 Trend Studies Using Artificial Urban Environments

The creation of artificial cities allows the isolation of certain sensitivities of the urban dose distribution to building geometries. An example of a dose distribution from artificially constructed city geometry is shown in Figure 2-8. The buildings are all the same FEMA Hazus building type (S2H, Steel Braced Frame) and have identical 120 m x 60 m footprints. The north-south streets are twice as wide as are the east-west streets. The center buildings out to a radius of 300 m are 250 m tall and the rest of the buildings are 10 m tall. The parameters of building height, footprint size and road width can be changed in isolation to see how the urban-to-open ratio relation to individual components of the average zone elevation.

A study of a set of these artificial cities is shown in Figure 2-9. Each city has a separate, but uniform, building height. All the cities have the same street structure (similar to the one in Figure 2-8) and the same building type. The center streets (the ones that cross at the detonation location) are slightly different road widths, ranging from 30 m wide to 90 m wide. Varying the road widths was done to better understand the effect the road structure had on the overall dose pattern. In the plot of all the cities, the general relationship between the urban-to-open-field ratio and the average zone elevation follows a decreasing urban-to-open-field ratio as average zone elevation increases. The locations with high urban-to-open-field ratios were identified as points on the edge of the center streets which have increased scattering from the higher particle flux down those paths.

In Figure 2-10, a plot of the urban-to-open field ratio versus the average zone elevation for a set of artificial cities with higher-elevation center buildings surrounded by lower buildings is depicted. Figure 2-5 is a graphic representation of one of these cities and Figure 2-8 is a neutron dose in one of those cities. This study used a 300 m radius of buildings in the center that were 250 m tall and a uniform set of buildings around it with elevations that varied by city. In the plot, there are sets of data labeled "500 m" which correspond to data sets where the radius of taller center buildings was expanded to 500 m. This data set also shows the trend of decreasing urban-to-open field ratio with average zone elevation, though the plot is less dramatic than the preceding plot. The 500-m radius of buildings shifts the dose ratio by only between 10-20% from that of the 300-m radius of taller buildings. There is a larger distribution of urban-to-open field ratio for a single value of average zone elevation at the higher average zone elevation, but the trend in the higher point density regions is evident. This study was repeated for center building heights, 170 m, 90 m, 60 m, 30 m and 20 m, which yielded similar trends. All artificial city test data are listed in Appendix C.

A study of the effect of different road widths on the urban-to-open-field ratio is shown in Figure 2-11. The 250-m-tall buildings in this study were kept the same while the streets throughout the artificial city were expanded from 30 m to 70 m. This is different from previous road width studies because all the roads in the cities were altered and not just the center roads. The ratio follows a similar trend to previous studies of varying the building heights showing that averaging both ground area and building elevations together is a valid method of representing building attenuation.

Finally, Figure 2-12 shows all of the artificial data sets created for this study plotted together. The plot weights all data points and data sets evenly, even though some studies contained many more data points than others. The results show a downward-sloping trend with some outlying data consisting of locations near the center streets. The homogenous building height study referenced in Figure 2-9 produces a more positive trend slope (evident from some data clusters above the central trend line), but the majority of the data from other studies is within 30% from the zone-elevation average of the overall trend.

A comparison of the artificial city data sets in Figure 2-12 with the more realistic scenarios in Figure 2-7 is shown in Figure 2-13. While a significant fraction of the data points lay over the general trend of the artificial data sets, the overall slope of the urban-to-open-field ratio versus average zone elevation is more negative for the more realistic urban scenarios than the artificial city data. It is not clear what characteristics of the realistic scenarios determine the slope. A single fit of the artificial city data output produces an overall average/estimated urban-to-open field ratio that is systematically elevated compared to a specific Monte Carlo calculation; therefore additional degrees of freedom are needed to better fit the data. A detailed description of an improved fit method are presented in Section 2.10.

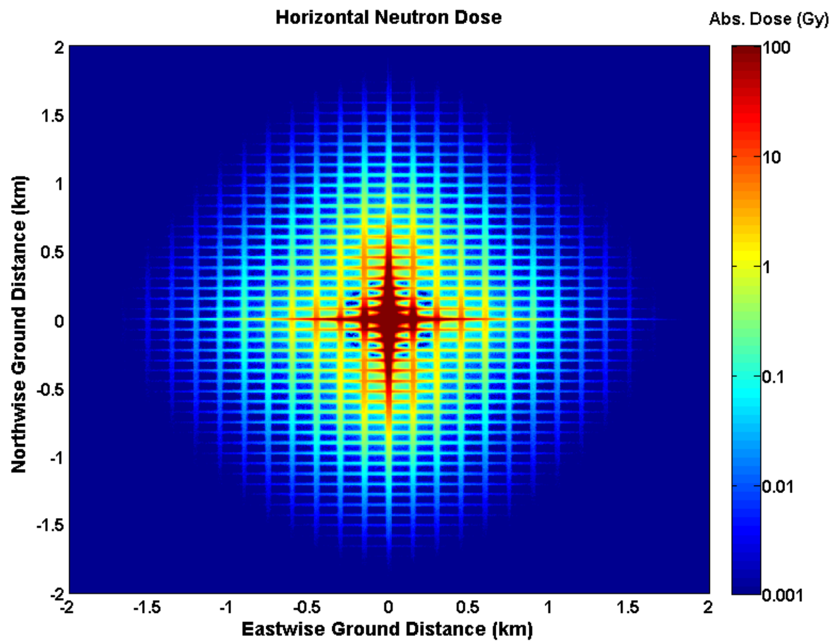

Figure 2-8. Neutron dose in artificial city geometry. The source is a 10-kT unshielded fission source 1-m above ground.

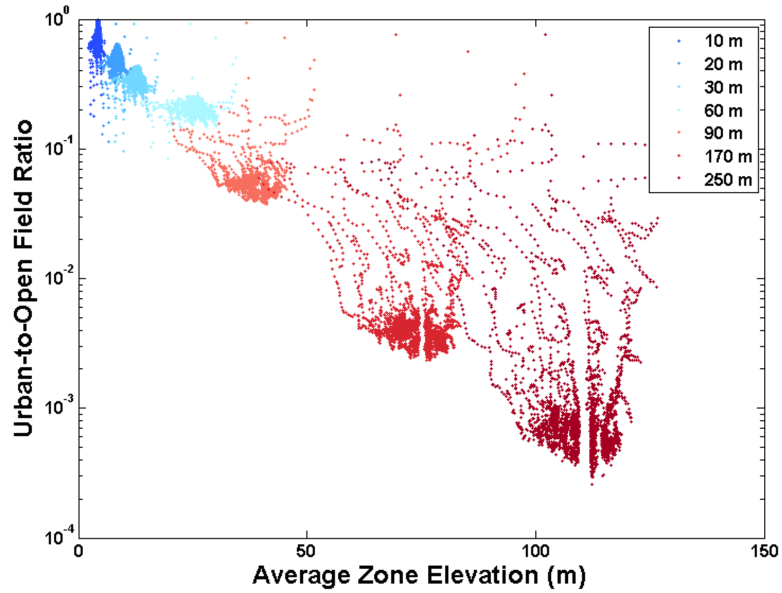

Figure 2-9. The neutron urban-to-open field ratio versus the average zone elevation for a set of artificial city runs where the buildings are all the same height

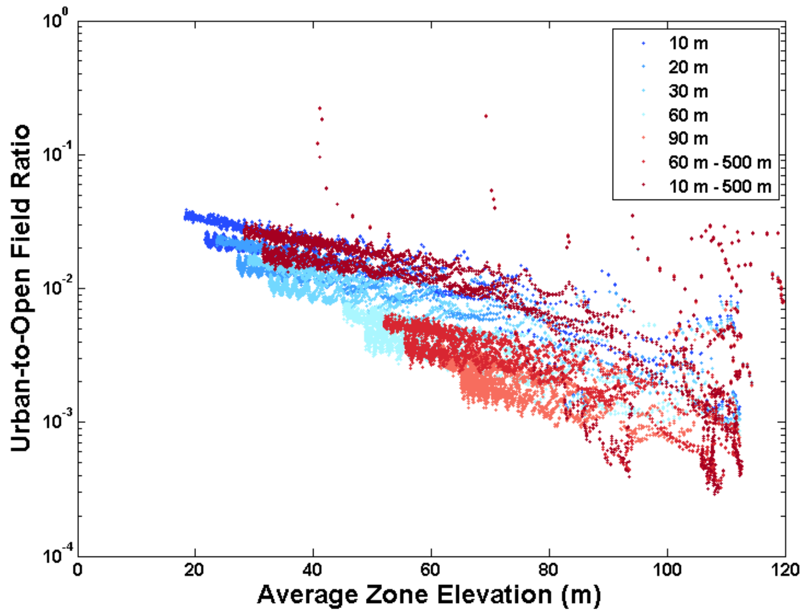

Figure 2-10. The neutron urban-to-open field ratio versus average zone elevation for a series of artificial cities

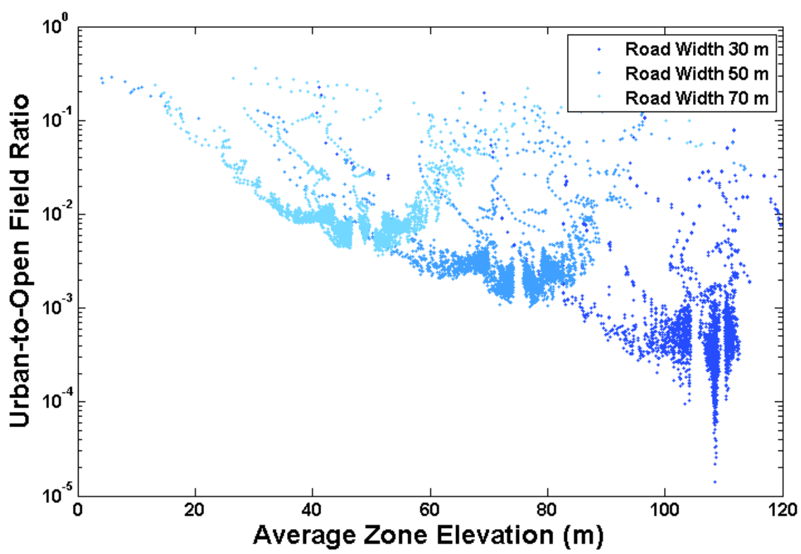

Figure 2-11. A study of increasing the road width while maintaining the same building height for three different cities for neutron dose

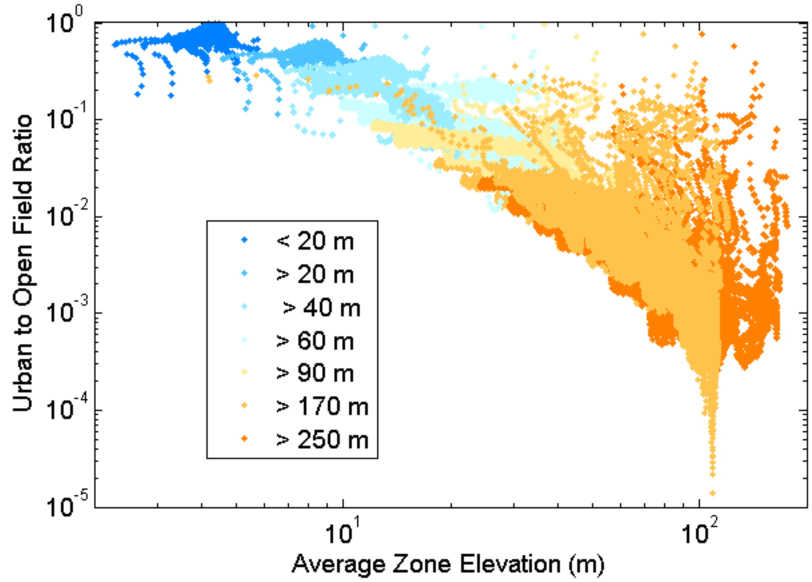

Figure 2-12. A plot of the neutron urban-to-open field ratio versus average zone elevation for all the artificial city data created for this report

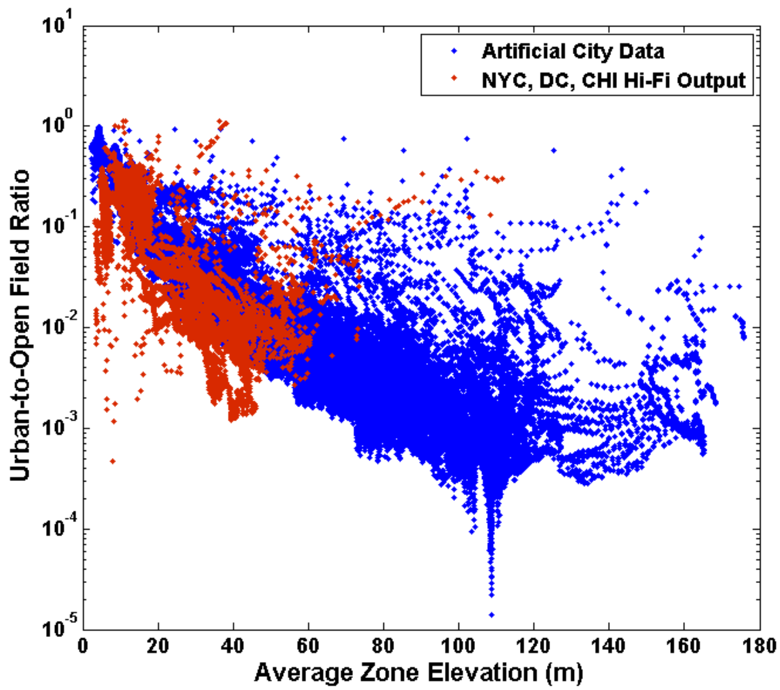

Figure 2-13. A plot of the neutron urban-to-open field ratio versus average zone elevation for all the artificial data with the addition of three sets of data from three different urban detonation scenarios

2.8 Degeneracy in Average Zone Elevation

In an attempt to improve the quality of the parameterization of the MCNP dose, the issue of degeneracy within a single average zone elevation value was studied. The issue is illustrated by Figure 2-14. The green rectangles represent buildings, the yellow circles are the detonation location and the red circle is the location of the simulated dose measurement. The top scenario, with the three tall buildings, has the same average zone elevation as the lower scenario, with the eight smaller buildings, that is, both scenarios are degenerately described by the identical average zone value. Figure 2-15 displays the degeneracy in the urban-to-open field ratio for a single average zone elevation.

Many different ways of breaking the degeneracy in these scenarios were evaluated before an efficient method was developed. The most effective method of breaking the degeneracy was to sort the artificial city data into different groups based on the tallest building height in the zone and generate separate parameters. ZEPrompt uses six different maximum-building-height groups to separate the different physical scenarios. The parameter associated with the maximum building height within a zone is applied to the dose calculations within that zone. The height groups corresponding to the different maximum heights in the artificial city data are detailed in Appendix C.

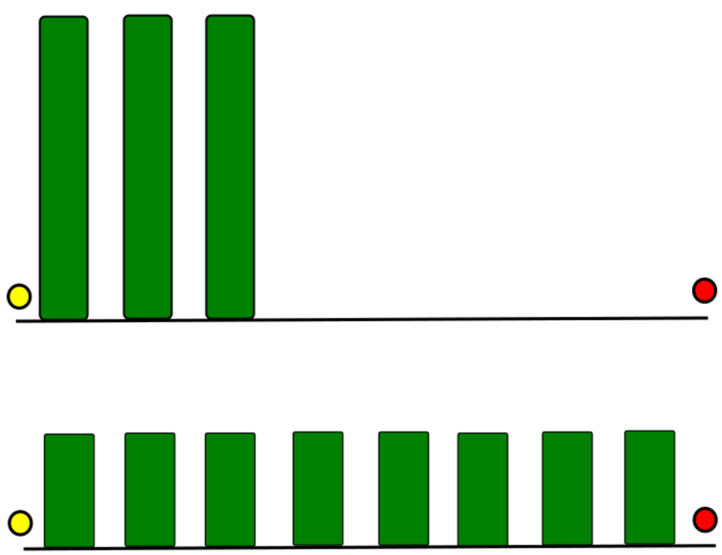

Figure 2-14. A graphic depicting degeneracy of the average zone elevation

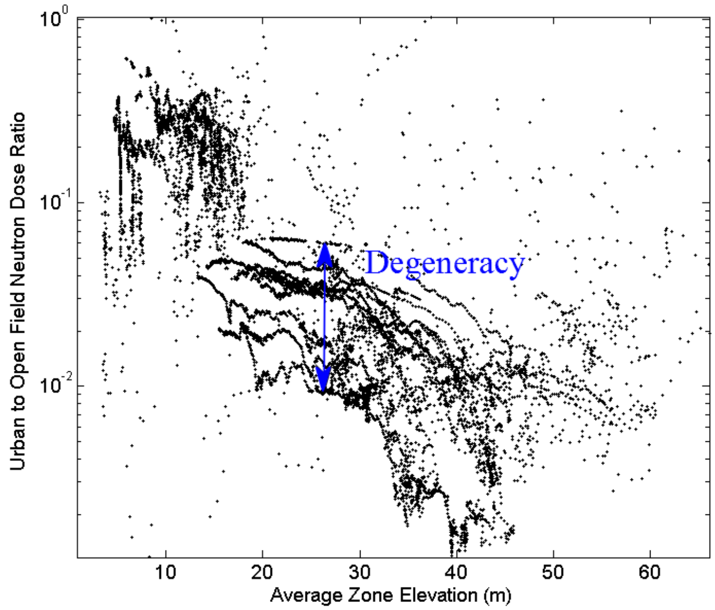

Figure 2-15. An illustration of the degeneracy in the urban-to-open-field neutron dose ratio for the average zone elevation in a Monte Carlo simulation of a realistic city building model

2.9 Roads and Other Direct Line of Sight Locations

Thus far areas in direct line of sight of the source have been excluded from consideration. These locations are primarily roads passing through the detonation location and open spaces near the detonation and are excluded because these areas follow a different relation between the urban-to-open-field ratio and the average zone elevation. The line-of-sight locations are defined as those that have less than 10 m of building material between the detonation location and the point at which the dose is being calculated. A plot of the artificial city data sets with only the points meeting the less than 10 m of scattering material is shown in Figure 2-16.

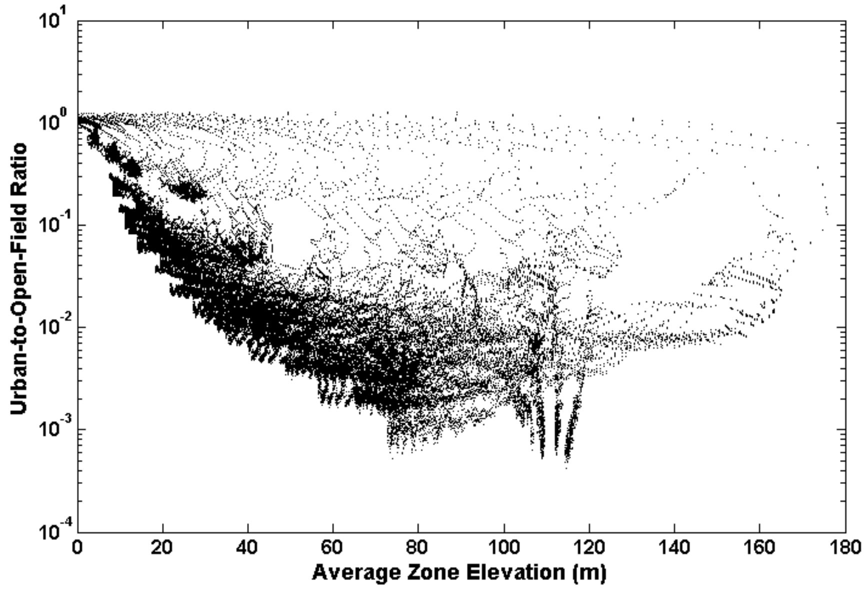

Figure 2-16. Urban-to-open field ratio versus average zone elevation for points that have direct line-of-sight or nearly-line-of-sight of the detonation location

2.10 Fitting the MCNP Output

To parameterize the dose data of the MCNP calculations, a power law relation was to fit the base-10 logarithm of the urban-to-open-field ratio. The function used was

$$F = 10^{\alpha \bar{E}^{\beta}} \qquad (3)$$

where F is the urban-to-open-field ratio, $\bar{E}$is the average zone elevation and α and β are fit parameters. This form was chosen because the urban-to-open ratio approaches unity in the limit of zero average zone elevation and because the ratio falls off smoothly even when the fit data is sparse. For this parameterization, the artificial city data sets are divided into groups by the highest building heights between the detonation and the location of interest resulting in α and β values for both photon and neutron particles that are uniquely associated with each of the highest building height groups.

The MCNP simulation created for this work calculates photon dose from both primary and secondary photons. The primary photons are generated from the source. The secondary photons are the product of neutron capture and generate greater than 95% of the absorbed photon dose from prompt radiation at survivable injury ranges. Therefore, the photon doses from both primary and secondary photons are combined and there is only one set of α and β values for photon dose even though the primary and secondary photons follow different trends.

The fits were performed using the urban-to-open-field dose ratio data from the combined artificial cities and excluded the more realistic urban data sets. The MATLAB curve-fitting tool with the Trust Region method was used (MathWorks, Inc., 2002). The fits are shown as red lines in Figure 2-17 (neutron) and Figure 2-18 (photon) with the artificial city data in black and the

more realistic city data plotted in blue for comparison. Table 2-1 list the six sets of parameters used for neutron and photon fits.

The fit of the direct line-of-sight and nearly direct line-of-sight data set did not benefit from the division into groups by maximum building height. There is a different set of fit parameters from the artificial city data for direct line of sight data for both neutron and photon data sets. The fits and the data are shown in Figure 2-19.

The effect of using separate fits for building-height groups can be seen in Figure 2-20. The neutron urban-to-open-field ratio is plotted for the MCNP calculation of the realistic New York City building model and is compared to two different parameterizations to the neutron artificial city data. The red line is the result of the fit procedure presented above where there are separate parameter sets for each of the maximum-building-height groups. The blue line represents a parameter set determined from the non-height-discriminated single fit to the artificial city data as described in Section 2.7 and shown in Figure 2-12. One can see improvement of the parameterization for the red line compared to the NYC data set in the top two plots. In the middle left plot, one can see both parameterizations are not matching the data well, but the six-function parameterization is closer to the data sets. The improved parameterization means nearly an order of magnitude improvement in the fit matching the urban-to-open-field ratio of the MCNP data in some places in NYC. This is due to having a different curve for areas with a large number of very high buildings.

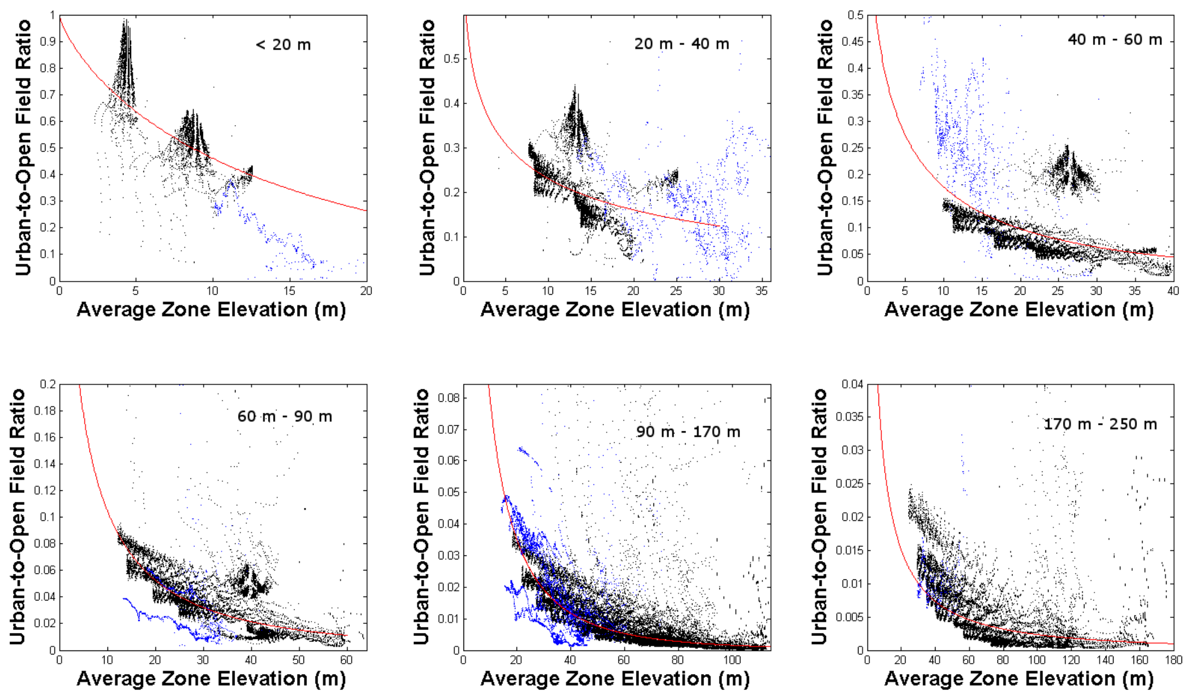

Figure 2-17. Six fits to the artificial city neutron data sorted into groups by maximum building height (range displayed in corner). Black points are from the artificial city data calculations. Blue points are from realistic urban models

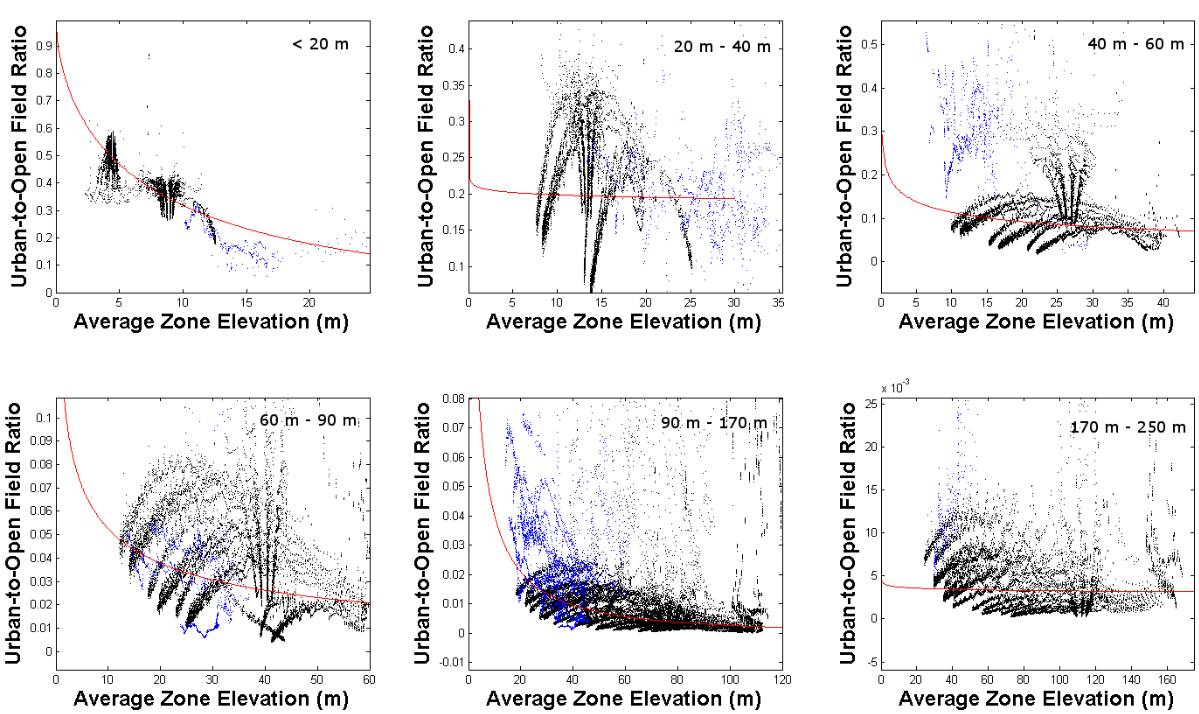

Figure 2-18. These plots are six fits to the artificial city photon data sorted into groups by maximum building height (range displayed in corner). The black points are from the artificial city data calculations. Blue points are from realistic urban models.

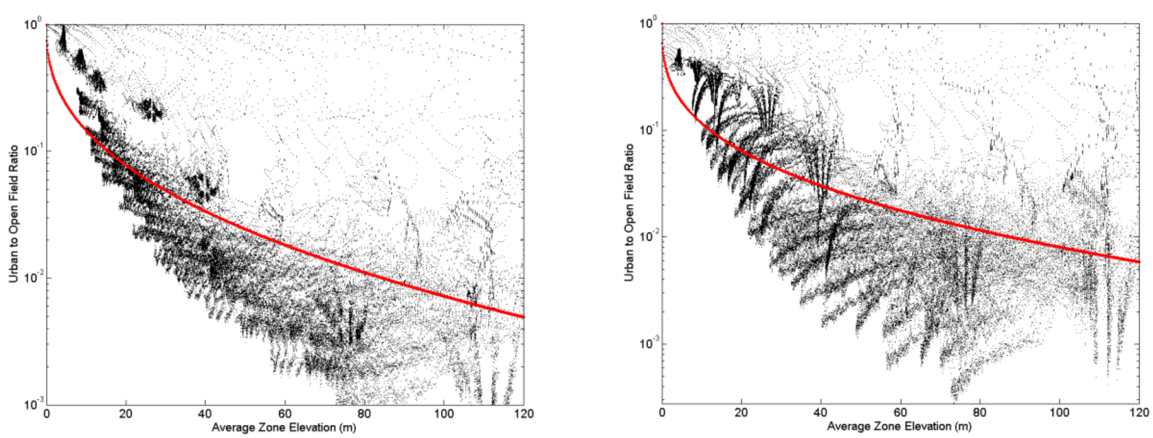

Figure 2-19. The fit to the direct line-of-sight neutron and photon data, respectively, from artificial cities data sets

Table 2-1. A list of the fit parameters used in the ZEPrompt Algorithm

Maximum Building Height (m)	α_n	β_n	α_γ	β_γ
250	-0.9214	0.2274	-2.374	0.009862
170	-0.4333	0.4051	-0.7585	0.2651
90	-0.4047	0.3838	-0.8998	0.1529
60	-0.2864	0.4199	-0.6918	0.1344
40	-0.3041	0.3209	-0.678	0.0148
20	-0.0562	0.7782	-0.678	0.0148
Line of Sight	-0.3264	0.4086	-0.4174	0.3502

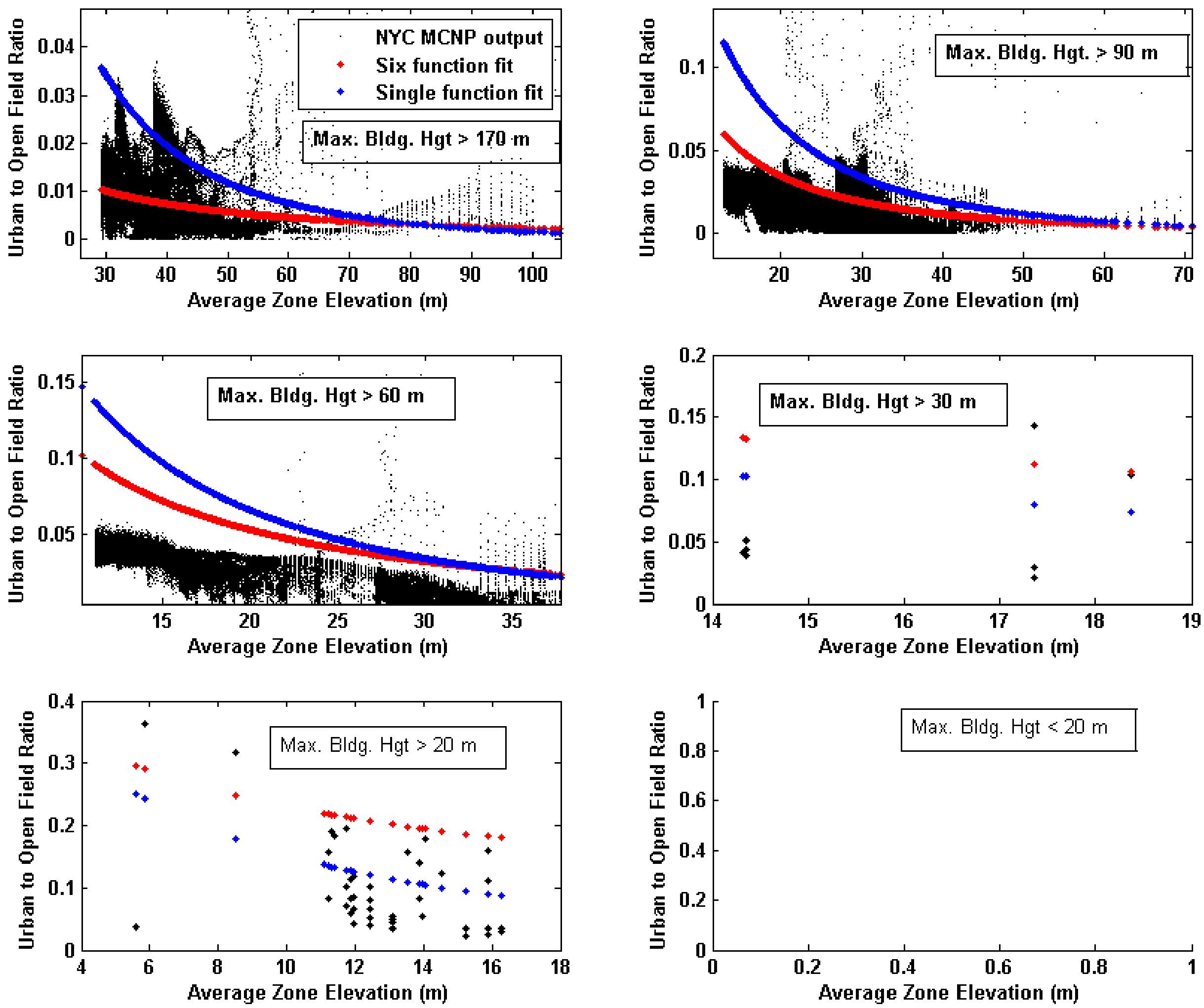

Figure 2-20. These are plots of the neutron urban-to-open-field ratio from MCNP for the New York City scenario. The red line corresponds to the six-function parameterization and the blue to a single-function parameterization.

Section 3.

Results and Estimation of Uncertainty

3.1 ZEPrompt and MCNP Dose Visual Comparison

The ZEPrompt calculations require less than 30 seconds on a dual-core 3.06-GHz PC and the results will now be compared to the dose from an MCNP calculation that requires approximately 6000 CPU-hours. The dose shown below follows the formula to combine the neutron and photon dose that uses a midline internal dose approximation and a quality factor for the neutrons:

$$D_{EQ} = C_{\text{int}}(Qd_n + d_\gamma) \qquad (4)$$

where D_{EQ} is the equivalent total prompt radiation dose, C_{int} is an estimated conversion factor from an external tissue dose to a midline internal tissue dose (the value used was 0.7 (Defense Nuclear Agency, 1979)), Q is the quality factor for the neutron (the value used was 3.0 from studies of neutron deterministic effects to the gastrointestinal tract (International Commission on Radiological Protection, 1989)), d_n is the neutron absorbed dose calculated in this report and d_γ is the calculated total photon absorbed dose.

Figure 3-1 through Figure 3-4 show side-by-side gridded absorbed dose from high-fidelity MCNP5 simulation with dose from the ZEPrompt algorithm. All sources are 10-kT unshielded fission yields at 1-m height of burst (Terrell, 1990).

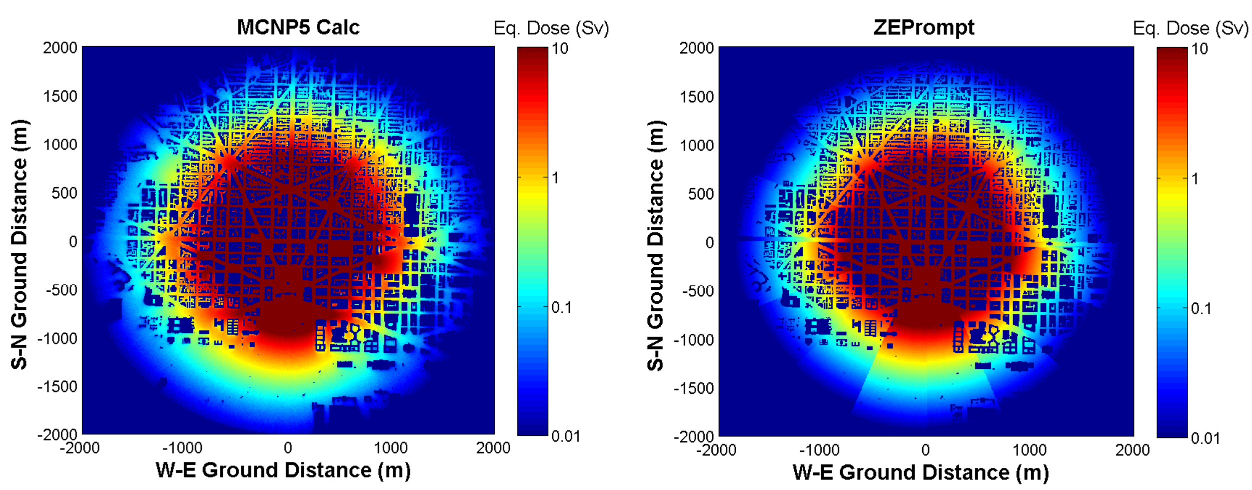

Figure 3-1. A comparison of a high-fidelity MCNP5 calculation with a ZEPrompt algorithm calculation in Washington, DC

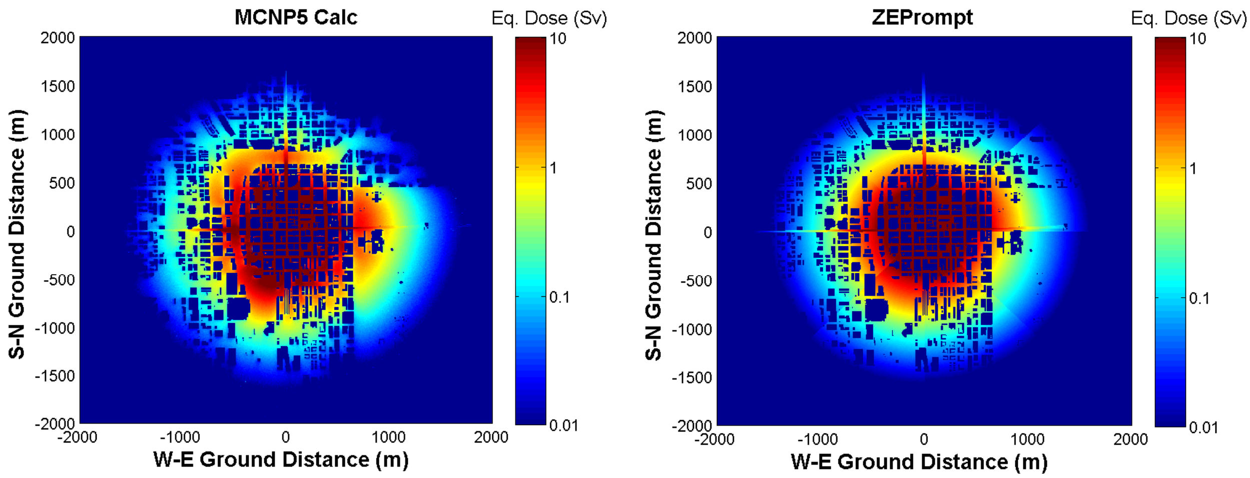

Figure 3-2. A comparison of a high-fidelity MCNP5 calculation with a ZEPrompt algorithm calculation in Chicago

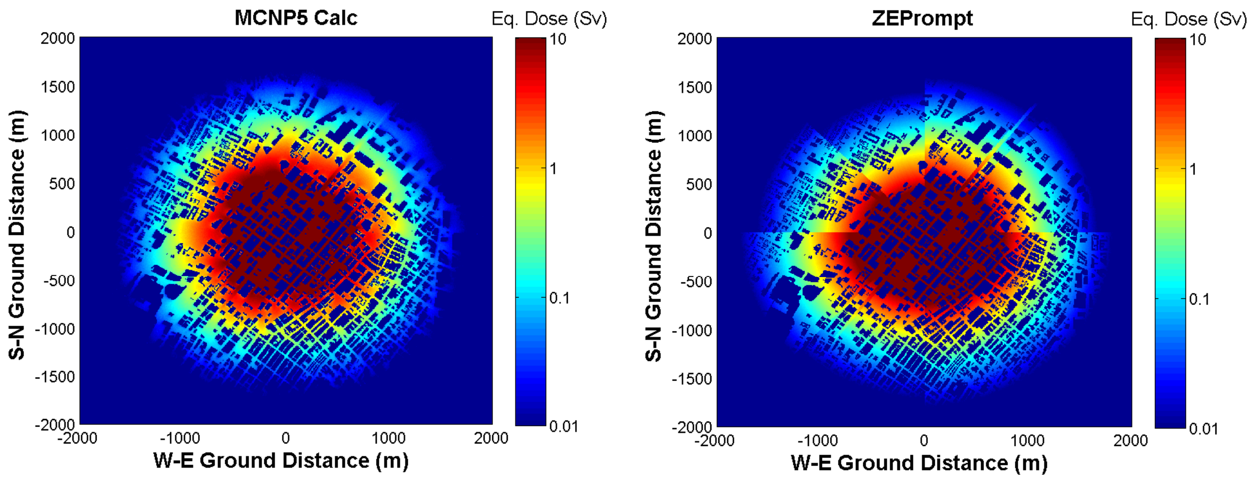

Figure 3-3. A comparison of a high-fidelity MCNP5 calculation with a ZEPrompt algorithm calculation in Los Angeles

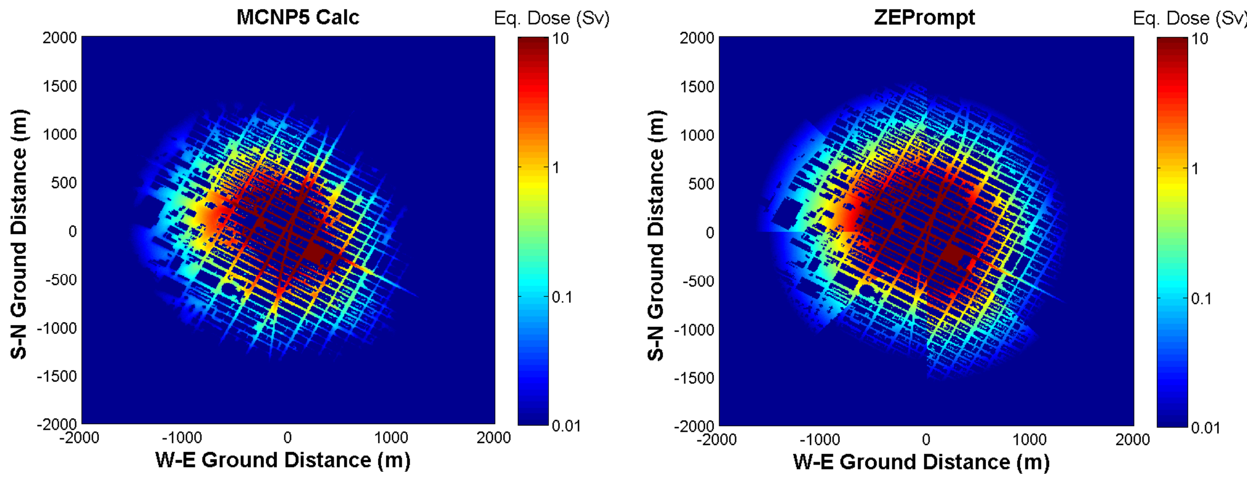

Figure 3-4. A comparison of a high-fidelity MCNP5 calculation with output a ZEPrompt algorithm calculation in New York City

3.2 Estimating Uncertainty in ZEPrompt

While a visual inspection reveals that ZEPrompt is producing dose that is qualitatively similar to the MCNP dose, a more thorough quantitative uncertainty analysis is warranted. A practical and intuitive way of estimating the quality of the parameterization of ZEPrompt with respect to the MCNP dose is to calculate and compare the distances from the source to various dose levels for both ZEPrompt and the MCNP and see how the values are affected by different city geometry, source types and yields.

The dose levels used for this analysis are 4.1 Sv, 0.75 Sv and 0.05 Sv absorbed dose calculated with both neutron and photon absorbed dose using Equation 4. These values were purposefully designated as 4.1 Sv is the LD50/60 for acute radiation dose, 0.75 Sv is considered the lower dose threshold of the presence of symptoms from acute radiation, and 0.05 Sv is a level meant to represent a lower threshold for delayed radiation effects. While ideally a different formula for combined dose should be used for delayed effects and acute effects to account for the different neutron biological damage mechanisms, the same formula is used for the sake of simplicity.

Since the MCNP output is tallied into 5-m x 5-m x 1-m voxels, some averaging is necessary to get the estimated dose level range in terms of constant radius from the detonation location. The averaging is done for a single circular wedge by finding the closest arc of constant radius from the detonation location in each circular wedge with an average outside-of-building dose lower than the target dose level. The differences between the two dose levels is represented as

$$\Delta R = R_{MCNP} - R_{ZEPrompt} \qquad (5)$$

where R represents the distance from the detonation location to the closest arc of the dose level of interest.

Plots of the MCNP dose color-coded into four sections are shown in Figure 3-5 through Figure 3-7. The yellow-green color represents the area where the combined neutron and photon dose calculated by MCNP is > 4.1 Sv. The cyan color is for combined dose > 0.75 Sv. The light blue area is for combined dose > 0.05 Sv and the dark blue is the remaining region. Buildings are also represented as dark blue. There are three sets of arcs that represent the ZEPrompt dose level ranges for the 16 sectors plotted here. The dark red arcs represent where the ZEPrompt level is 4.1 Sv. The bright red arcs represent where the ZEPrompt dose is at 0.75 Sv and the yellow arcs are where the ZEPrompt dose levels are at 0.05 Sv.

The Washington, DC plot shows visually similar agreement between the dose-level ranges of MCNP and ZEPrompt, with some differences at longer range. The Chicago comparison is more complicated, but the average dose level is similar, even if the variance is higher between the two calculations. ZEPrompt overestimates the range to the dose levels in New York City for most sectors as compared to the other cities.

Below, in Table 3-1 through Table 3-4, a quantitative analysis of the dose level ranges for MCNP and ZEPrompt are presented. The average $\Delta R = R_{MCNP} - R_{ZEPrompt}$ for the 16 sectors is calculated for each scenario, with a particular source and a particular yield designated for each. The MCNP Dose Range is the average dose level range for all 16 sectors. Both an absolute average difference and average relative differences (to the MCNP average dose level range) are listed in the tables.

In Table 3-5, several combined averages for the dose level differences are shown. The first is an average of the four city models with the same source and yield. The second is seven different Washington, DC scenarios averaged together. The third is eight New York City scenarios averaged together. The standard deviation of both of those quantities is included with the mean absolute difference and the mean relative differences.

Figure 3-8 shows histograms of the relative range differences of the four city models using only the 10-kT unshielded fission source. Each histogram contains entries from each of the 16 sectors from the four different scenarios for a total of 64 sectors on each plot. These histograms show the distribution of the range differences for each dose level for a single sector.

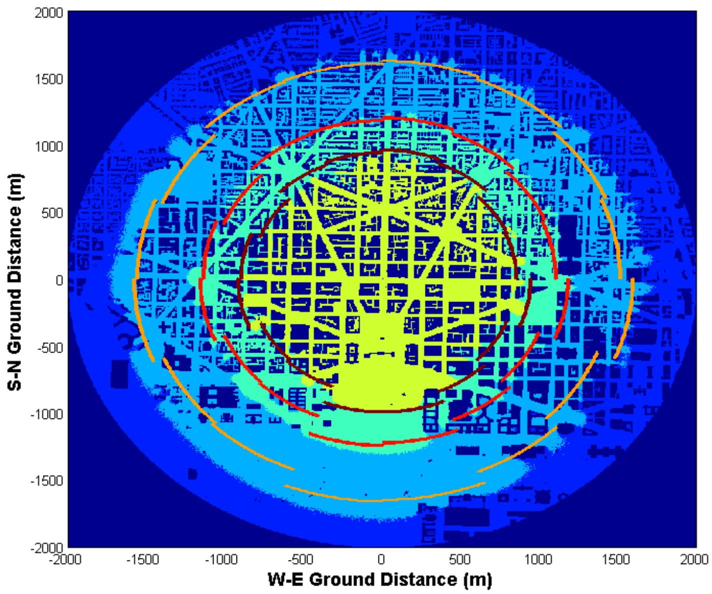

Figure 3-5. A comparison of dose ranges of MCNP and ZEPrompt in the Washington, DC model

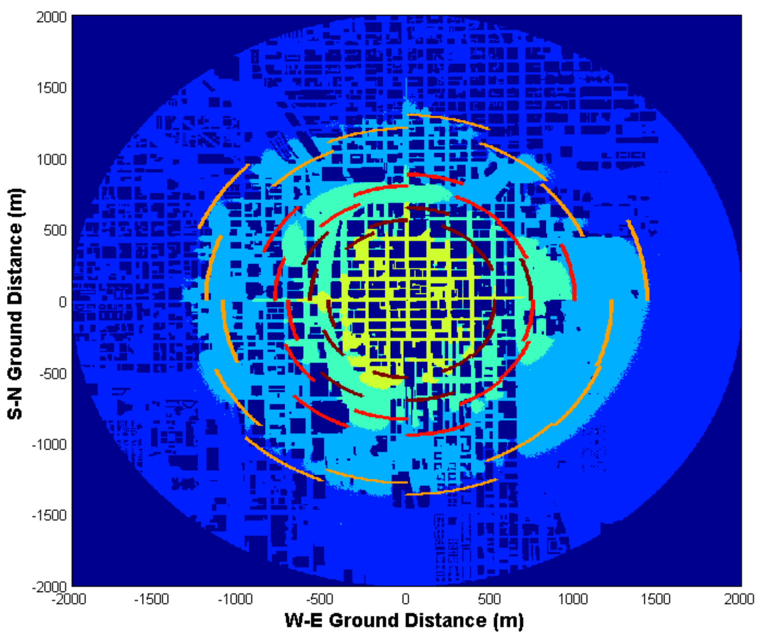

Figure 3-6. A comparison of dose ranges of MCNP and ZEPrompt in the Chicago model

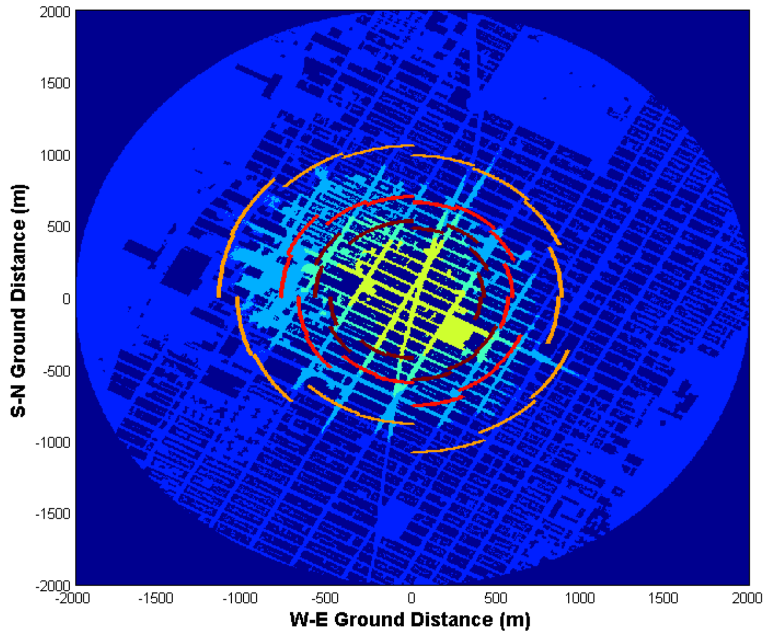

Figure 3-7. A comparison of dose ranges of MCNP and ZEPrompt in the New York City model

Table 3-1. A comparison of dose ranges of MCNP and ZEPrompt in the Washington, DC model

City Model	Source	Yield (kT)	Eq. Dose (Sv)	MCNP Dose Range (m)	Mean ΔR (m)	Mean ΔR (%)
Wash., DC	Unshielded Fission	10	4.10	971	56	5.7
		10	0.75	1221	66	5.4
		10	0.05	1670	98	5.8
	'Little Boy'	10	4.10	724	16	2.1
		10	0.75	934	35	3.6
		10	0.05	1331	36	2.4
	'Fat Man'	10	4.10	494	-34	-7.4
		10	0.75	714	-50	-7.8
		10	0.05	1213	-58	-5.5
	Thermo-nuclear	10	4.10	1148	118	10
		10	0.75	1453	145.6	10
		10	0.05	1960	163	8.3
	Unshielded Fission	5	4.10	857	2.0	0.2
		5	0.75	1114	25	2.2
		5	0.05	1550	59	3.7
	'Little Boy'	16	4.10	773	-9.4	-1.4
		16	0.75	996	17	1.6
		16	0.05	1429	34	2.0
	'Fat Man'	22	4.10	581	-60	-11
		22	0.75	828	-81	-11
		22	0.05	1389	-66	-5.7

Table 3-2. A comparison of dose ranges of MCNP and ZEPrompt in the New York City model

City Model	Source	Yield (kT)	Eq. Dose (Sv)	MCNP Dose Range (m)	Mean ΔR (m)	Mean ΔR (%)
New York City	Unshielded	10	4.10	503	-108	-23
		10	0.75	723	-108	-16
		10	0.05	1071	-150	-15
	‘Little Boy’	10	4.10	393	-88	-24
		10	0.75	521	-121	-25
		10	0.05	825	-124	-16
	‘Fat Man’	10	4.10	298	-34	-17
		10	0.75	400	-53	-20
		10	0.05	665	-144	-28
	Thermo-	10	4.10	606	-82	-15
	nuclear	10	0.75	854	-83	-10
		10	0.05	1293	-98	-8.5
	Unshielded	5	4.10	438	-89	-21
	Fission	5	0.75	629	-114	-19
		5	0.05	983	-137	-15
	‘Little Boy’	16	4.10	434	-85	-20
		16	0.75	568	-122	-23
		16	0.05	871	-142	-17
	‘Fat Man’	22	4.10	344	-41	-19
		22	0.75	456	-81	-24
		22	0.05	783	-167	-25
	Thermo-	50	4.10	846	-80	-10
	Nuclear	50	0.75	1101	-98	-9.8
		50	0.05	1626	-62	-4.4

Table 3-3. A comparison of dose ranges of MCNP and ZEPrompt in the Chicago model

City Model	Source	Yield (kT)	Eq. Dose (Sv)	MCNP Dose Range (m)	Mean ΔR (m)	Mean ΔR (%)
Chicago	Unshielded	10	4.10	610	-38	-6.1
	Fission	10	0.75	869	-3.1	0.78
		10	0.05	1299	17.5	1.2

Table 3-4. A comparison of dose ranges of MCNP and ZEPrompt in the Los Angeles model

City Model	Source	Yield (kT)	Eq. Dose (Sv)	MCNP Dose Range (m)	Mean ΔR (m)	Mean ΔR (%)
Los	Unshielded	10	4.10	750	-8.1	-1.4
Angeles	Fission	10	0.75	988	10	1.2
		10	0.05	1367	8	0.72

Table 3-5. A combined data set analysis of the dose level ranges differences between MCNP and ZEPrompt

City Model	Source	Yield (kT)	Eq. Dose (Sv)	Mean ΔR (m)	Mean ΔR (%)	Std. Dev. ΔR (m)	Std. Dev. ΔR (%)
All 4	Unshielded	10	4.10	-20.3	-5.5	115	19
City	Fission	10	0.75	-8.6	-2.4	117	14
models		10	0.05	-6.5	-1.8	129	11
All 7	All four	Various	4.10	39	2.6	72	8.9
DC	sources		0.75	49	2.8	94	9.3
Models			0.05	60	2.8	120	8.2
All 8	All four	Various	4.10	-78	-20	89	22
NYC	Sources		0.75	-91	-18	94	20
models			0.05	-129	-17	125	19

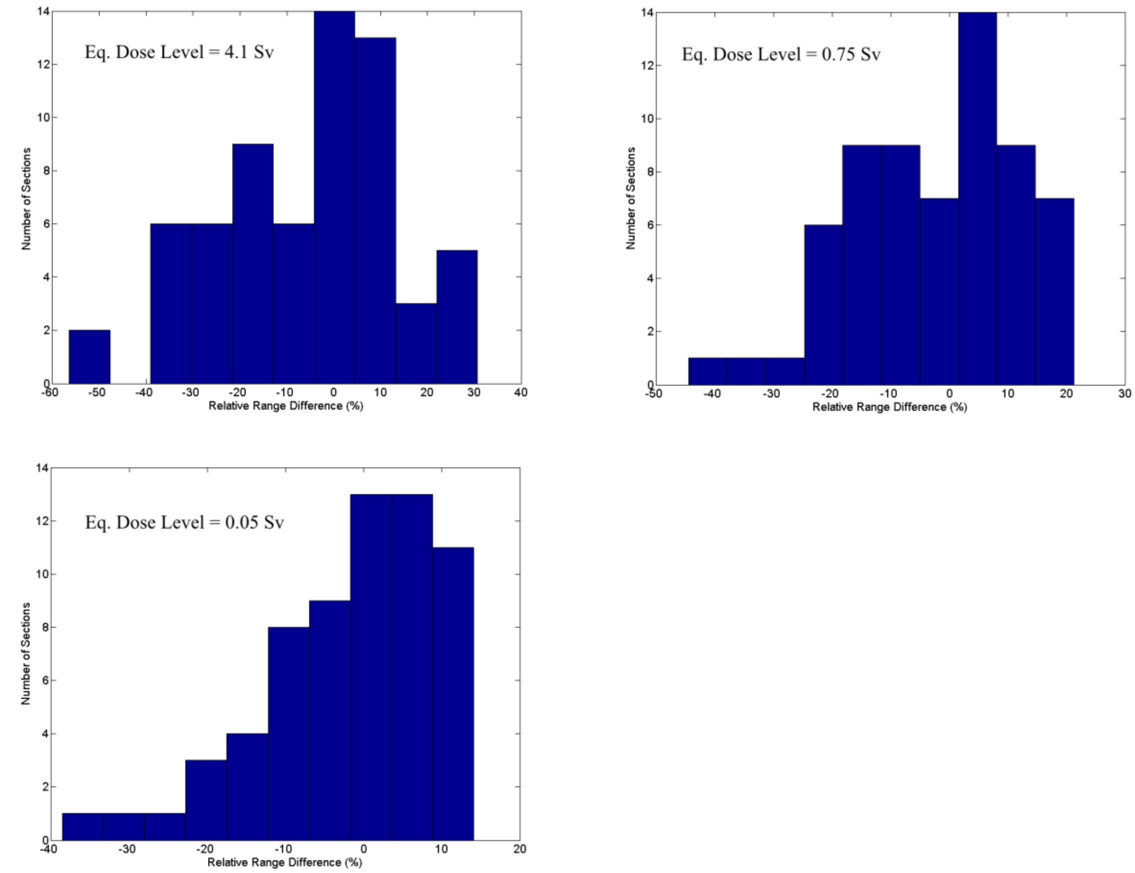

Figure 3-8. Histograms of the relative range difference between sector-averaged dose ranges of MCNP and ZEPrompt

Section 4.

Conclusions and Model Limitations

ZEPrompt is a fast-running tool that is based on parameter fits to previously calculated high-fidelity Monte Carlo calculations. The MCNP calculations for an ensemble of artificial city models were used to create an algorithm to estimate the prompt radiation neutron and photon dose in an urban environment using the urban geometry and an open-field calculation of the source. ZEPrompt calculates this dose in less than a minute on a standard PC and the sector-averaged dose level ranges are accurate within 30% for more complicated city scenarios such as Manhattan and less than 10% for more homogeneous cities such as Washington, DC.

ZEPrompt is only intended for 1-m height-of-burst calculations over flat terrain and has been used for ranges of less than 2 kilometers with approximated sources between 5 kT and 50 kT. ZEPrompt has been tested solely for the range of devices presented in "A Summary of Unclassified Leakage Spectra for the Purpose of Simulating the Prompt Radiation from a Nuclear Device*."* (Kramer K. M., 2012), but these devices may not cover the full range of possible source spectra. ZEPrompt also has only been tested against the city scenarios presented in this report.

ZEPrompt has only been tested for the initial radiation released before the device disassembles. ZEPrompt does not attempt to include the delayed radiation from the decay of fission fragments and other sources of radiation. The delayed radiation is an important contribution to the total radiation, and this radiation should be included in a future methodology.

ZEPrompt is intended for the quick generation of prompt radiation dose maps that could be used as a part of planning scenarios, casualty estimations and other assessments where reasonable approximation will satisfy requirements. However, ZEPrompt would not be appropriately suited for situations where more detailed analysis is necessary.

Future work will develop parameter sets for various heights of burst and potentially extending the ground range of the calculation to account for higher yields. In addition, the tool will be developed for stand-alone use as well as integrated into DTRA consequence assessments codes.

Section 5.

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Appendix A
Neutron and Photon Source Terms

This report used four different unclassified source spectra. The neutron and photon source spectra are shown here in Figure A-1 and Figure A-2. The normalizations from yield to particles are listed in Table A-1.

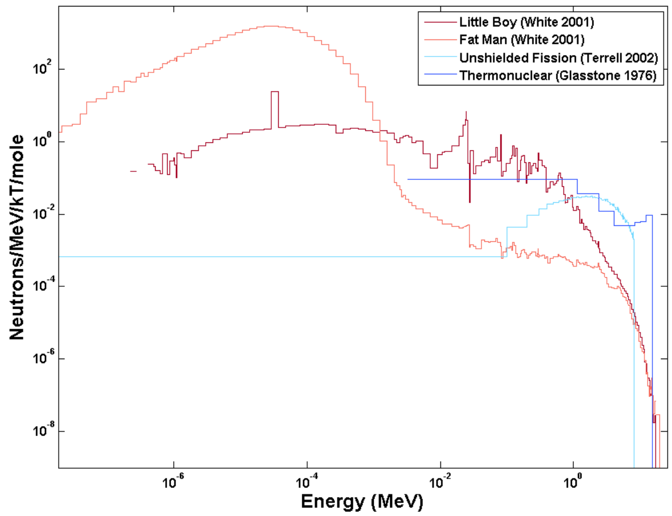

Figure A-1. Neutron spectra for all sources presented in this document

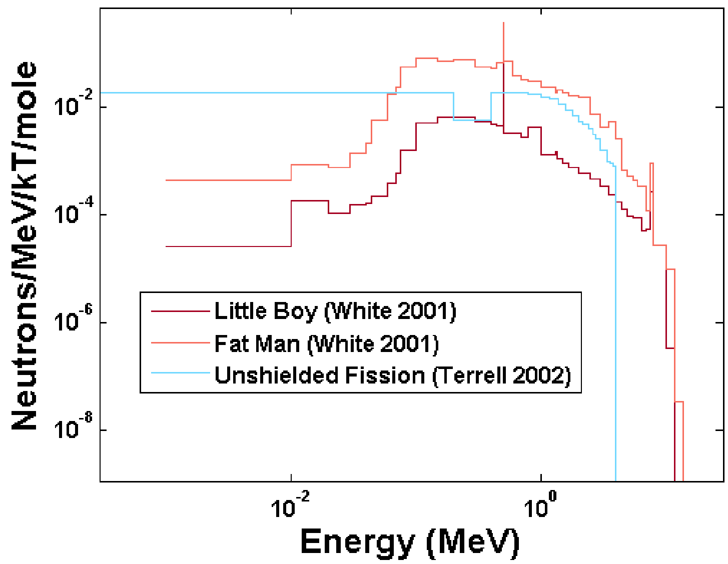

Figure A-2. A plot of the photon spectra for all sources presented in this document. The unshielded fission spectra is used both for the unshielded fission source and for the thermonuclear source.

Table A-1. A list of the yield-to-particle normalization constants for the sources in this report

Source Name	Source Neutrons ($x10^{22}$)/ kT	Source Photons ($x10^{22}$)/kT
Little Boy (White, 2001)	1.08	0.401
Fat Man (White, 2001)	15.9	7.29
Unshielded Fission (Terrell, 1990)	7.57	9.81
Thermonuclear (Glasstone, 1977)	14.4	1.88

Appendix B
Elevation Maps of Urban Geometries

This report uses four different urban models for testing. The four figures shown below represent building height maps of the modeled urban environments. The detonation location is at the center point (0 m, 0 m) on these maps. The elevation represented by the color bar is in meters.

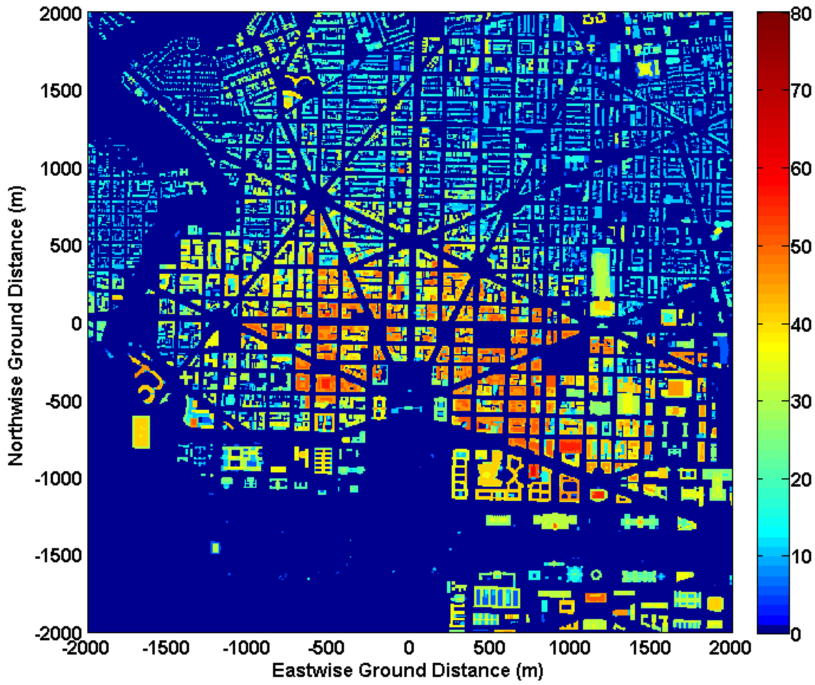

Figure B-1. Elevation map of the Washington, DC model

Figure B-2. Elevation map of New York City model

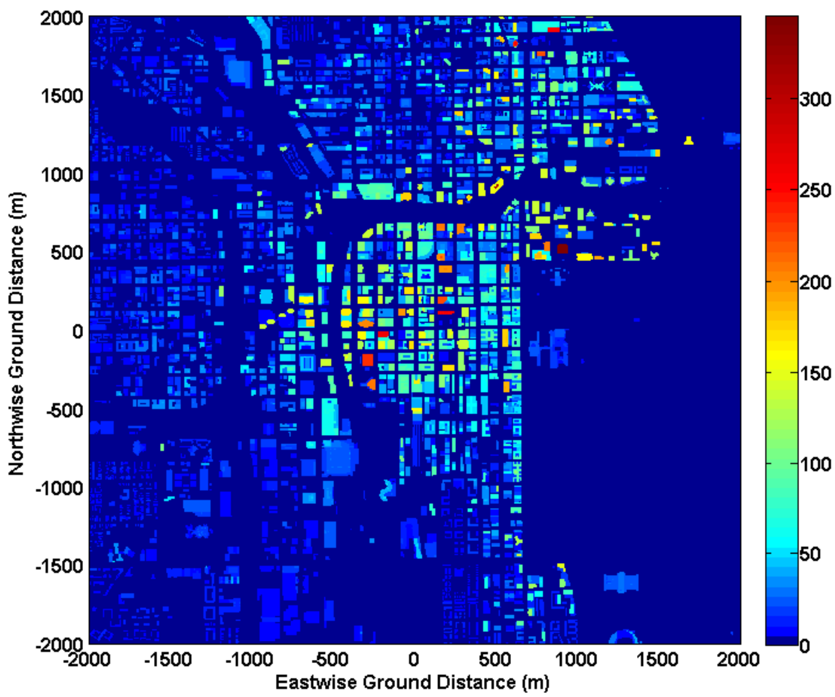

Figure B-3. Elevation map of the Chicago model

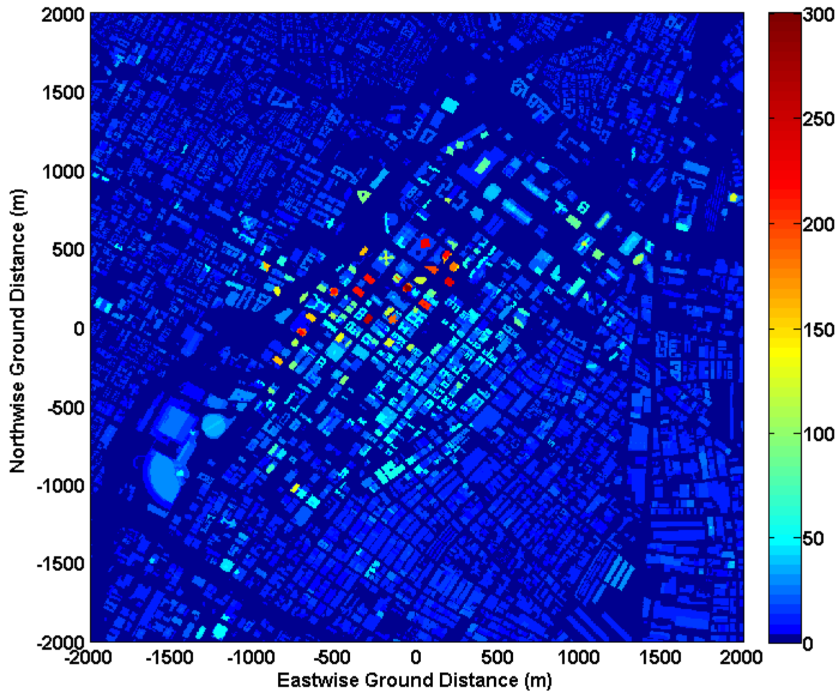

Figure B-4. Elevation map of Los Angeles model

Appendix C
Description of Artificial Cities

Three different basic building footprints were used to make the artificial cities used in this report. The first is shown in Figure C-1, which was used for the homogeneous building elevation tests. This model had center roads of differing widths, as shown in Figure C-2. The second artificial city footprint is shown in Figure C-3, where the center buildings (green) within a 300 m radius are taller than the rest of the buildings (grey) in the artificial city. The third, shown in Figure C-4, is similar to the second model, only with a 500 m radius section of buildings in the center.

A list of all the MCNP input decks (with the HSRD IPT internal input deck name listed for reference) created for the artificial cities is shown in Table C-1. The artificial cities never have more than two building heights in the model, and homogeneous cities would just have one. All artificial cities used for analysis were of the same Hazus building type (Type S2, Steel-Braced Frame building).

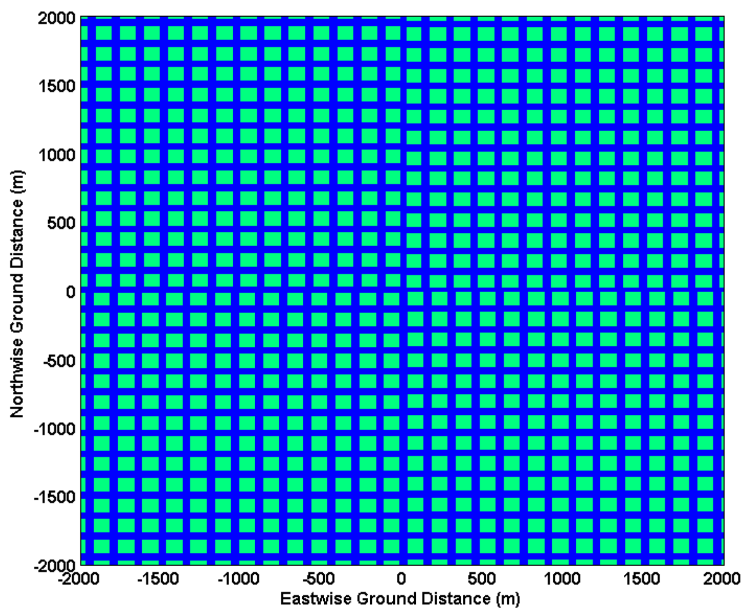

Figure C-1. The building footprint for the homogeneous artificial city models

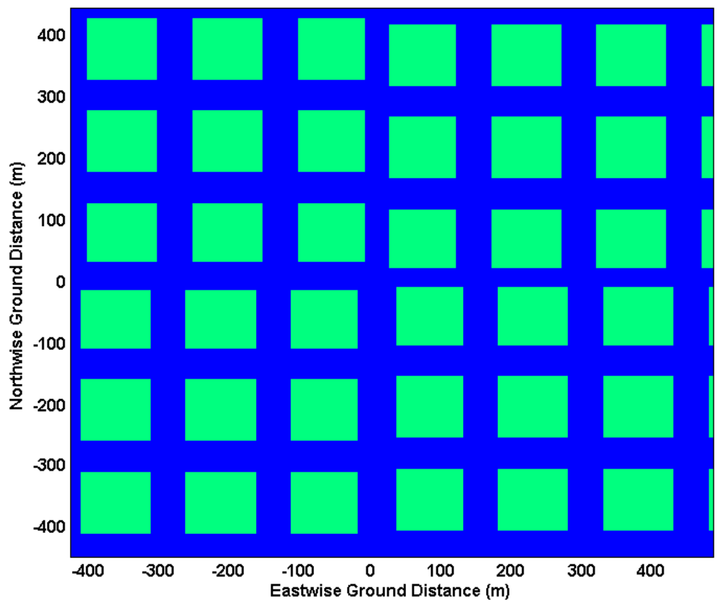

Figure C-2. A close-up of the center roads for the homogeneous artificial city footprint

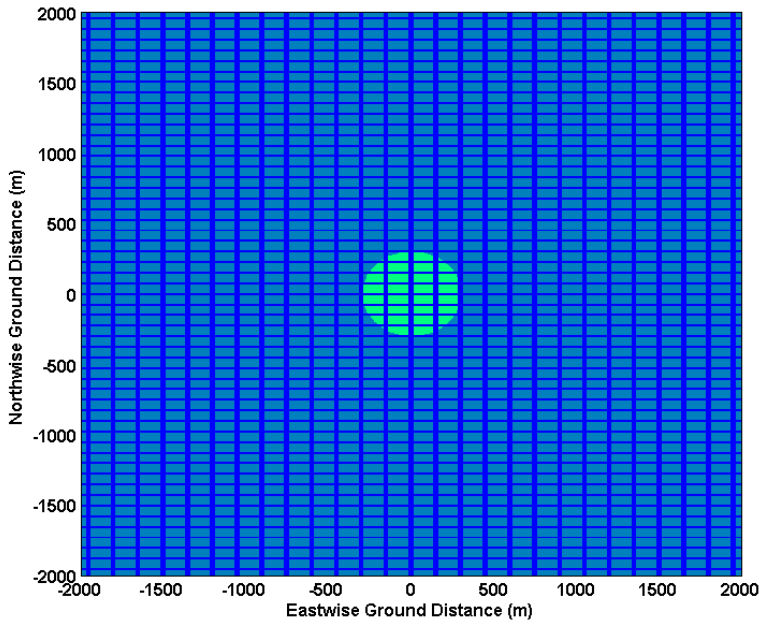

Figure C-3. The second type of artificial city building footprint used in the report

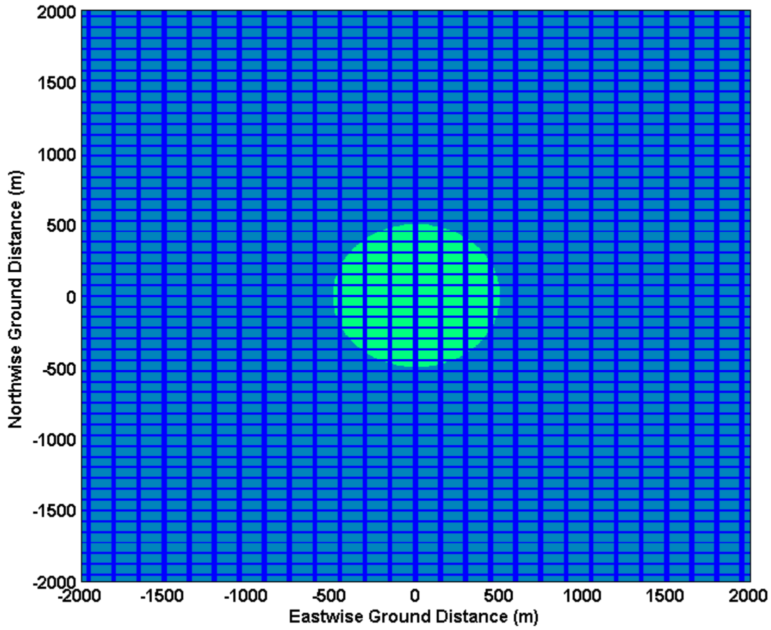

Figure C-4. The third artificial city building footprint

Table C-1. Description of the artificial city input decks used in analysis

HSRD IPT input deck name	Footprint	Max. Building Height (m)	Min. Building Height (m)	Notes
TSTgguc7B	Figure C-1	10	10	
TSTgguc7C	Figure C-1	20	20	
TSTgguc7D	Figure C-1	30	30	
TSTgguc7E	Figure C-1	60	60	
TSTgguc7F	Figure C-1	90	90	
TSTgguc7G	Figure C-1	170	170	
TSTgguc7H	Figure C-1	250	250	
TSTggucCB	Figure C-3	20	10	
TSTggucDC	Figure C-3	30	20	
TSTggucDB	Figure C-3	30	10	
TSTggucED	Figure C-3	60	30	
TSTggucEC	Figure C-3	60	20	
TSTggucEB	Figure C-3	60	10	
TSTggucFE	Figure C-3	90	60	
TSTggucFD	Figure C-3	90	30	
TSTggucFC	Figure C-3	90	20	
TSTggucFB	Figure C-3	90	10	
TSTggucGF	Figure C-3	170	90	
TSTggucGE	Figure C-3	170	60	
TSTggucGD	Figure C-3	170	30	
TSTggucGC	Figure C-3	170	20	
TSTggucGB	Figure C-3	170	10	
TSTggucHG	Figure C-3	250	170	
TSTggucHF	Figure C-3	250	90	
TSTggucHE	Figure C-3	250	60	
TSTggucHD	Figure C-3	250	30	
TSTggucHC	Figure C-3	250	20	

TSTggucHB	Figure C-3	250	10	
TSTggucG0	Figure C-1	170	170	Road Width = 30 m
TSTggucG1	Figure C-1	170	170	Road Width = 50 m
TSTggucG2	Figure C-1	170	170	Road Width = 70 m
TST5gucGF	Figure C-4	170	90	
TST5gucGE	Figure C-4	170	60	
TST5gucGD	Figure C-4	170	30	
TST5gucGC	Figure C-4	170	20	
TST5gucGB	Figure C-4	170	10	

Abbreviations, Acronyms, and Symbols

ARA	Applied Research Associates, Inc.
AZE	Average Zone Elevation
CHI	Chicago
CPU	Central Processing Unit
DNA	Defense Nuclear Agency (United States)
DTRA	Defense Threat Reduction Agency (United States)
FEMA	Federal Emergency Management Agency (United States)
Gy	Gray
Hi-Fi	High Fidelity
HSRD	Human Survivability Research and Development
ICRP	International Commission on Radiological Protection
IPT	Integrated Program Team
kg	kilogram
km	kilometer
LD50/60	Lethal Dose for 50% of population after 60 days
LIDAR	Light Radar, a remote sensing technology
m	meter
MCNP	Monte Carlo N-Particle radiation transport software
NCR	National Capital Region
NGA	National Geospatial Intelligence Agency
NYC	New York City
Sv	Sievert
U.S.	United States
ZE	Zone Elevation